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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**AN ANALYSIS OF THE DEFENSE ACQUISITION
STRATEGY FOR UNMANNED SYSTEMS**

by

Courtney David Jones

March 2014

Thesis Co-Advisors:

Nicholas Dew
William Fast

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**AN ANALYSIS OF THE DEFENSE ACQUISITION STRATEGY FOR
UNMANNED SYSTEMS**

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ABSTRACT

In the past 12 years of sustained conflict, the Department of Defense (DoD) has procured thousands of unmanned systems, from ordnance disposal robots to airborne surveillance platforms to unmanned cargo helicopters. These assets have saved countless lives and have become critical to DoD strategy. The health of the U.S. robotics industry must become a national strategic imperative in order to maintain technology dominance.

The cyclical nature of DoD funding inevitably results in industry expansion and consolidation. The unmanned systems industry will be subject to consolidation pressures. Keeping unmanned system cost-per-copy low is critical; thus, economies of scale should be highly valued. However, premature robotics industry consolidation could threaten innovation and competition that will be critical for the U.S. military to maintain its dominance.

With impending budget reductions, there will be increasing pressure to narrow down on robotics technologies to achieve efficiencies and reduce costs. However, to maintain the health of the robotics industry, the acquisition strategy must be contingent on the evolution of industry. This thesis examines the defense robotics industry and historical technology S-curves for comparable industries and evaluates unmanned system acquisition strategies.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	three-dimensional
A2/AD	anti-access/area denial
AMLCD	active matrix liquid crystal display
APUC	acquisition program unit cost
ASD(R&E)	Assistant Secretary of Defense for Research and Engineering
AUVSI	Association for Unmanned Vehicle Systems International
BLOS	beyond line-of-sight
CASIC	China Aerospace Science & Industry Corporation
CBRNE	chemical, biological, radiological, nuclear, and high-yield explosives
CJCS	Chairman of the Joint Chiefs of Staff
CRUSER	Consortium for Robotics and Unmanned Systems Education and Research
CRS	Congressional Research Service
DAMIR	Defense Acquisition Management Information Retrieval
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DHS	Department of Homeland Security
DTIC	Defense Technical Information Center
EMI	electromagnetic interference
EPC	electronic product code
FAA	Federal Aviation Administration
FY	fiscal year
GAO	Government Accountability Office
GMe	General Microelectronics
HEL	high-energy laser
ICBM	intercontinental ballistic missile
ICD	Initial Capabilities Document
IR&D	independent research & development
IT	information technology

JCIDS	Joint Capabilities Integration Development System
JROC	Joint Requirements and Oversight Council
JSF	Joint Strike Fighter
JUON	Joint Urgent Operational Need
KPP	Key Performance Parameters
LEMV	Long Endurance Multi-Intelligence Vehicle
MDA	Milestone Decision Authority
MFD	multifunctional display
MOS	metal-oxide-semiconductor
MSA	Material Solutions Analysis
MURAL	Manned Unmanned Resupply Aerial Lifter
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NPS	Naval Postgraduate School
O&M	operations and maintenance
O-DMAS	On-Demand Medium Area Surveillance
OIS	optical imaging systems
OSD	Office of the Secretary of Defense
PBL	Performance-Based Logistics
PLA	People's Liberation Army
PM	Program Manager
PSC	product service code
RAA	Rapid Acquisition Authority
RCS	radar cross section
REF	Rapid Equipping Force
RFID	radio frequency identification
RDT	rapid deployment training
RDT&E	research, development, testing and evaluation
R&D	research & development
S-Curve	sigmoid curve
SABR	Scalable Agile Beam Radar
SATCOM	satellite communications

SECNAV	Secretary of the Navy
SLAM	simultaneous localization and mapping
SME	subject matter expert
S&T	science & technology
TRA	Technology Readiness Assessment
TRANSEC	transmission security
TRL	Technology Readiness Level
UAS	unmanned aerial system
UAV	unmanned aerial vehicle
UMS	unmanned maritime systems
USAF	United States Air Force
USD(AT&L)	Under Secretary of Defense for Acquisition, Technology, & Logistics
USG	United States government
USMC	United States Marine Corps
USN	United States Navy
UUV	unmanned underwater vehicle
VHSIC	very high speed integrated circuit
VTOL	vertical takeoff and landing
WWI	World War I
WWII	World War II

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I. INTRODUCTION

The past 12 years of international conflict have resulted in amazing breakthroughs in the way the Department of Defense (DoD) envisions the role of unmanned systems. Several factors have led to this dramatic increase in interest in unmanned systems, chief among them the evolving nature of unconventional warfare and the increasing focus on casualty avoidance. The wars in the Middle East have been a boon for the U.S. robotics industry, which has benefitted from yearly increases in DoD research and development (R&D) spending. The common refrain, “the last fighter pilot has already been born,” carries a lot of weight for the robotics industry, which has moved to the forefront of strategic initiatives.

The proliferation of unmanned systems on the battlefield has not been without issue. In the haste to field game-changing new technologies, the DoD has distributed a lot of money among many companies to field the most advanced equipment. Some argue that money has been wasted developing technologies that other companies figured out but would not share due to proprietary constraints (Government Accountability Office, 2006). This has led to much scrutiny of the acquisitions process, where increasing focus on cost savings and avoidance will put pressure on decision-makers to narrow down quickly on proven technologies in order to achieve efficiencies. If this narrowing down on technologies occurs before technological maturity, the DoD runs the risk of losing technological dominance in the battlespace and could face even greater costs in upgrading and retrofitting outdated technologies.

Steele (1989) noted that in corporate firms, strategic management is often in conflict with operations management. He stated that survival depends on balancing the tension between current operational fiscal needs and the need to fund research and development to maintain technological dominance. He also noted the twin demons of technology management: cost effectiveness and certainty of performance (Steele, 1989). Certainty of performance is of even greater importance in military applications. Although an important characteristic of unmanned systems is relative expendability, the DoD

should explore all reasonable measures to ensure certainty of performance, to make sure as many unmanned systems return to base as possible.

Tsipis and Janeway (1984) discussed a quandary in which procurement specialists often find themselves. At the time, they noted, the U.S. was in the process of purchasing 7,000 M1 tanks at a cost of \$20 billion, but many argued that the U.S. should focus on building 20,000 cheaper tanks. However, the second choice would require additional crews to man and maintain the tanks, driving up manpower costs. Currently, the manpower requirement is sometimes greater for unmanned systems than for manned systems, given the infancy of autonomy technology. However, the defense roadmaps envision a future where autonomous control and more efficient systems greatly reduce manpower requirements.

The increased DoD focus on energy efficiency also bodes well for unmanned systems proliferation. Studies have shown that not only are unmanned aviation systems cheaper per copy than manned systems that perform similar missions, but the unmanned systems also burn a fraction of the fuel (Null, 2010).

After almost 100 years of evolution in the fixed-wing aviation industry, the F-35 Joint Strike Fighter (JSF) is the epitome of the desires for economies of scale, but it is the only major program of its kind in production at this moment. While the JSF was designed to be the most versatile multi-role fighter/attack aircraft yet, one has to wonder how much innovation and competition has been sacrificed in an attempt to gain economies of scale. Initially the program promised unprecedented commonality between the versions produced for each service, but that has not been the case. Cost overrun has been another major problem with the JSF and other platforms. The rush to low-rate production prior to technology maturation has resulted in millions of dollars spent in retrofit (GAO, 2012).

This report draws a distinction between *exploration* and *exploitation*. According to Benner and Tushman (2002), “exploitative innovations involve improvements in existing components and build on the existing technological trajectory, whereas exploratory innovation involves a shift to a different technological trajectory” (p. 679). *Exploration* determines the bounds of technology and determines which trajectory to

take. *Exploitation* refers to taking the superior technology and maximizing it, achieving efficiencies and incremental improvements that make the technology better and hopefully cheaper to produce. The terms *exploration* and *exploitation* are used throughout the report.

Budget data for unmanned systems through 2018 seem to indicate that the DoD is trending toward exploitation, rather than further exploration (*IHS Jane's Budget Analysis for FY14*, 2013). Although labeled a strategic priority, unmanned systems R&D and procurement budgets are relatively flat or in decline. The industry is as healthy now as at any point in history, with around 40 companies receiving funds for unmanned system development. Attempts to achieve efficiencies could irreparably harm the U.S. unmanned systems industry and result in a loss of competition and innovation critical to maintaining dominance.

There will be intense pressure for defense robotics industry consolidation as fiscal pressures mount in the coming years. However, attempting to compress the time frame between exploration and exploitation may lead the DoD into long-term procurement contracts for technologically inferior products. The defense acquisition strategy for unmanned systems procurement must balance short-term cost avoidance pressures with the need for investment in long-term technological advantage.

A. PURPOSE OF THE RESEARCH

The purpose of this thesis is to compare unmanned systems technology evolution and acquisition strategies to historical examples to develop a framework that supports future acquisition policy.

B. RESEARCH QUESTIONS

1. What are the evolutionary similarities between the unmanned systems industry and early aviation and information technology (IT) industries?
2. How is DoD funding distributed across firms in the U.S. robotics industry?
3. Does the DoD procurement strategy for unmanned systems promote industry innovation and competition?

4. Does the proposed defense budget demonstrate the importance placed on the unmanned systems industry development?

C. BENEFITS OF THE RESEARCH

This research attempts to place the unmanned systems evolution in context of other technological evolutions to help defense leaders develop a strategy that promotes competition and innovation in the unmanned systems industry.

D. LIMITATIONS OF THE RESEARCH

This research does not cover classified unmanned systems application and therefore, cannot present findings on many of the technological advances underway in the robotics industry.

The difficulty in forecasting and assessing technological breakthroughs also limits the comparative analysis of technology S-curves. While it is easy to assess the impact of historical technological breakthroughs, the impact of future breakthroughs is limited only by the imagination and cannot be accurately weighted in context of historical precedent.

E. SCOPE AND RESEARCH METHOD

This research consists of a comparative analysis of the present unmanned systems industry with historical industry examples to identify similarities in the evolution of innovation. Using the historical analysis, this report develops a framework for comparison dealing with industry evolution and the effects of government policies on innovation.

F. ORGANIZATION OF THE RESEARCH REPORT

In the first section of this research report, Chapter II examines the evolution of technology in various industries to provide a framework for comparison. Chapter III discusses the methodology used for the comparative analysis between the industries. The next section, Chapter IV, examines the current state of the unmanned systems industry in the U.S. Chapter V presents a comparative analysis of the unmanned systems industry with the industries discussed in Chapter II. Chapter VI presents a comparison of the Office of the Secretary of Defense (OSD) Unmanned Systems Integrated Roadmap

(Office of the Secretary of Defense, 2013) with future budget info to draw conclusions. The last section analyzes the DoD's unmanned systems acquisition strategy and recommends policies to maintain innovation and competition in the unmanned systems industry.

G. SUMMARY

Unmanned systems provide a cost-effective way to protect national security and U.S. service member lives. The DoD has opened up a world of possibilities with unmanned systems and must carefully manage the nation's resources to maintain technological dominance on the battlefield and around the globe.

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II. LITERATURE REVIEW

A. INTRODUCTION

In the first part of this literature review, I attempt to establish context for the evaluation of technology in order to draw parallels between the unmanned systems industry and historical industries. I examine common methods of estimating technology maturity, including technology S-curves and industrial systems evolution.

The second part of this literature review focuses on historical examples of technological evolution in the fixed-wing aviation and information technology industries. This report details the role of government research, development, technology, and evaluation (RDT&E) and procurement in the development of new technology.

B. CHARTING THE EVOLUTION OF TECHNOLOGICAL INNOVATION

1. Technology S-Curves

To establish context between evolutionary trends in technology, one must construct a framework for comparison. The framework can take many different forms but is most commonly associated with a learning curve, or technology S-curve (Sigmoid curve), due to its shape. Because most relevant literature approaches technological evolution from the standpoint of a company, in this analysis *the firm* refers to the DoD or individual service component, depending on who evaluates the unmanned system technology.

The S-curve is depicted in numerous ways but the most common depiction features product performance metrics in the y-axis and a time or effort component in the x-axis, as seen in Figure 1. The metric assigned to the y-axis is extremely important in objectively evaluating performance over a time period.

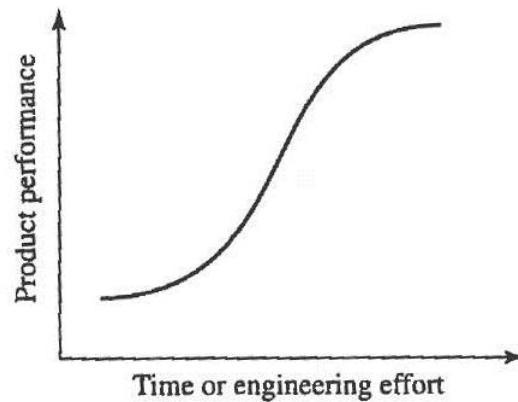


Figure 1. Technology S-Curve (from Christensen, 1999)

Researchers have described different facets of innovation in many ways. One dichotomy salient to this discussion is component versus architectural innovation. Christensen (1999) described architectural innovation as a change in the design or system of components, as opposed to a change in a component that makes up the system. Both component and architectural innovations follow S-curve patterns. In many industries, architectural innovations lead to the most dramatic upheavals in innovation, with Christensen (1992) noting that next generation architectural innovation is often inferior to the existing generation at first, which may make it initially seem like a poor strategic choice. Figure 2 shows the overlap between generations of architectural innovation. Christensen (1992) noted that entrant firms, not dominant firms, are often responsible for major architectural innovations.

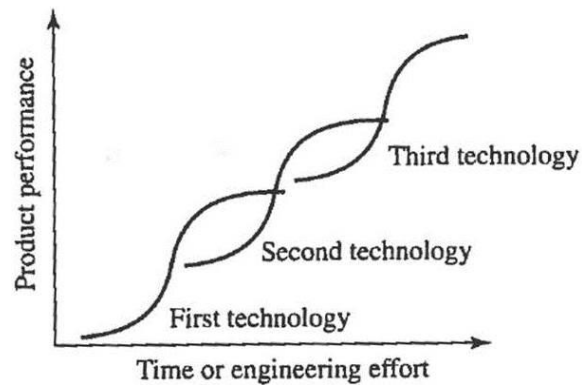


Figure 2. Multiple Technology S-Curves (from Christensen, 1999)

Christensen (1999) specified two strategies available to the firm when a technology approaches what appears to be the top of the S-curve. The firm can choose to switch to a new, more promising technology that has created a new S-curve in the diagram (as seen in Figure 2). The firm can also choose to stretch the life of the current technology by exploring ways to improve product components. The choice to switch or stretch is a strategic decision with many implications for the firm.

As Christensen (1999) noted, the chief drawback of using the technology S-curve to evaluate current technology is assuming the curve is leveling out near the top (technology maturation) when it is not. A firm might actually retard the further development of technology if it errs in its estimates and pursues counterproductive resource allocation by switching S-curves. Likewise, failure to correctly identify technological maturity may result in retaining the increasingly obsolete technology too long. Failure to adopt a strategy for switching technologies can result in the loss of technological dominance by a leading firm.

Christensen (1999) provided four recommendations for using S-curves to determine what strategy to pursue. First, benchmarking competitors' performance can provide a clear picture of technological maturity. The universality of performance metrics is critical to benchmarking. Second, Christensen accurately observed that technology maturation could be the result of a new innovation, rather than the cause of it. The launch of a revolutionary new technology could drive development away from a current

technology. Third, the component level offers many alternatives to switching S-curves, including stretching or improvements to system architecture. Fourth, identifying the need to switch S-curves is most critical at the architectural level, but it may be the more difficult analysis, since emergent architectural innovations are often less capable than the existing technology and may appear to be inferior (Christensen, 1992).

Christensen (1999) also drew parallels between the maturity of the nascent architectural technology and the speed with which it supplanted the old architecture, arguing that the more mature the nascent technology when it emerged, the quicker it replaced the old technology. He pointed to disk drive technology in the computer industry as evidence, stating that new architectural technology accounted for over 50% market share within two years of introduction, and the old technology had almost disappeared in four years. While this observation is solely related to disk drive technology in the 1990s, the trend is similar, if not accelerated, in many other technological fields. Dussauge, Hart, and Ramanantsoa (1992) described this phenomenon, pointing to the “snowball” (p. 19) effect of combinations of technologies that reduce “the delay between invention and commercialization by internalization of the R&D process” (p. 19).

The consequences for failing to recognize and switch to an emerging, dominant technology can be dire. As Mui (2012) noted, although Kodak invented digital photography technology, it failed to recognize it as a disruptive technology and focused its resources on film. As a result, the Kodak Company is today a shell of its former self. This is an example of the Schumpeterian model of creative destruction: A new technology appears that eventually destroys the old technology. However, it may take time for the complete obsolescence of the old technology to occur. As noted by Utterback (1996) in his discussion of the gas lamp industry in the late 1800s, the new technology may even spur the old technology to new heights as competition between the rival technologies increases. Early electric lamps, pioneered of course by Thomas Edison, immediately competed with entrenched gas lamps. The quality of the light from the earliest electric lamps, however, could not rival gas lamps, and the appearance of the electric light spurred the gas lamp industry to important innovations that improved efficiencies and lowered costs in the gas lamp industry (Utterback, 1996).

Another depiction of technological innovation (Dussauge et al., 1992) could be its effect on unit cost. In this case, a learning or experience curve is depicted in a diagram with time or effort on the x-axis and unit cost on the y-axis (see Figure 3). Innovation would then be depicted as a curve where unit cost declines as time or effort increases, due to developments that bring down the cost of the product. As seen in the technology S-curve, the innovation curves overlap, signifying the higher unit cost of new technological developments compared to the existing technology. If the firm continues production of the old technology, eventually the firm is unable to bring unit cost down any further. A switch to the nascent technology might incur higher costs, but the potential of the technology exceeds the risk of switching. In this case, the firm has to choose between exploiting efficiencies with the current technology and switching to a new technology that might achieve considerably greater cost savings in the long run.

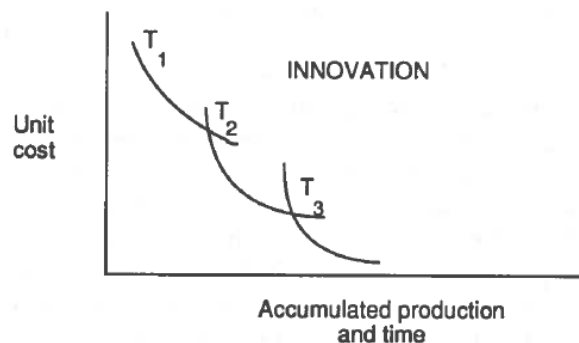


Figure 3. Innovation Curves and Unit Cost (from Dussauge et al., 1992)

The drawback to S-curves is that they are much easier to depict once the technological maturation is well in the past. Forecasting is the most difficult part of assessing technological capability. Technological forecasters can hazard a guess at a future capability but can never adequately explain how this capability can be achieved (Dussauge et al., 1992). This emphasizes the importance of meaningful metrics to assess advancement. For example, Moore's Law (Moore, 1965) is a famous estimate of hard drive storage capacity capabilities. It uses bytes per specified area of disk space as a metric for storage. Moore was able to forecast technological capabilities with surprising

accuracy but never specified how it was to be accomplished. Until a new data storage medium is constructed, this will continue to be the metric used to assess data storage capability. Here, Dussauge et al. (1992) pointed to the fact that while the amount of data per specified area has increased by one rate, the cost of storing a single unit of information has decreased by a different rate, which further compounds the problem of accurate forecasting. The single biggest impediment to accurate forecasting is the unforeseen technological discontinuity that creates a new S-curve and brings the previous one to an abrupt end as other firms seek first-mover advantage (Dussauge et al., 1992).

Perhaps the best approach toward forecasting is summed up by Dussauge et al. (1992):

Indeed, what is important in anticipating technological changes is less identifying the paths that are probable than preparing for less predictable radical changes that may totally upset the bases of competition and create the most significant threats or opportunities for the firm. (p.73)

A firm's acquisition strategy must be as ready for what cannot be known as it is for what it assumes will occur. One of the most difficult challenges a firm must face is deciding what resources it must commit to address what it cannot yet visualize.

Dussauge et al. (1992) also advised that before a firm can make a decision to switch technologies, the firm must know what technological capabilities it possesses. This technological audit can greatly assist a firm in evaluating its portfolio, critical to planning for future decision-making. The problem is that it is difficult to place a dollar value on technological capability or the pursuit of it. Balance sheets clearly state the amount of R&D spent over a year, but this figure alone is insufficient in assessing a firm's technological capability.

With the emergence of a technological discontinuity, an organization must categorize it to develop the appropriate response. Utterback (1996) provided three questions to evaluate the discontinuity. First, does the discontinuity pertain to an assembled or a non-assembled product? For example, in the unmanned systems industry, does a discontinuity pertain to a radically new vehicular design, or does it pertain only to a component of an existing vehicle, like an onboard sensor? Second, does the

discontinuity represent a substitution of an existing product, or does it define a brand new market? Last, for the established industry firms, is the discontinuity competence-enhancing or competence-destroying (Utterback, 1996)?

2. Industrial System Evolution

Duysters (1996) proposed a series of hypotheses to evaluate industrial system evolution, which is also useful in examining the U.S. robotics industry. The first hypothesis deals with conditions of market and technological uncertainty. In this phase, new technologies are funded by academia and government institutions. Programs like the Defense Advanced Research Projects Agency (DARPA) explore the boundaries of emergent technology, serving as an incubator. Duysters' second hypothesis deals with early movers who attempt to use technological innovations in an offensive strategy. Duysters referred to these companies as "opinion leaders" (p. 24) whose early offerings shape the dynamics of the emerging technology. The death rate of companies trying to prove their product is highest during this phase, as the emergent technology is shaped into something commercially desirable, lest it fall by the wayside.

Duysters' (1996) third hypothesis detailed the emergence of the basic design, decreasing technological uncertainty in the innovation and bringing more companies into the market. During this phase, incremental improvements to the technology increase rapidly as firms attempt to gain a competitive advantage through differentiation, cost, or some other metric. Often, the larger firms with greater economies of scale enter the market at this time, which begins to put pressure on smaller firms. Dussauge et al. (1992) noted that industries where technology is of greater importance display greater potential for economies of scale as firms are pressured to achieve sales volume. To achieve and maintain competitive advantage, especially in the defense industry, firms seek long-run contracts and high product volume. The experience effect is much more important in this case (Dussauge et al., 1992). In Duysters' (1996) fourth hypothesis, these larger firms outcompete the smaller firms as prices decrease and more customers enter the marketplace. Competition between firms usually leads to standardization of the product.

Brittain and Freeman (1980) noted that during this phase technological innovation is usually supplanted by process innovation as firms attempt to achieve efficiencies.

Duysters' (1992) fifth hypothesis detailed the decline of technological innovation as industry carrying capacity is reached and efficiency becomes the most important competitive weapon. This situation leads to Duysters' sixth hypothesis, where the decreased profit margins drive out all but the most efficient companies with one exception. The mass market creates niches that allow specialist organizations to creep in. During this phase, dominant industries usually must increase R&D spending to stretch the limits of the current technology. Often, these specialist firms are able to create competence-destroying innovations that undermine the dominant firms, who find themselves unable to shift technologies due to inertia. In Duysters' seventh and final hypothesis, this competence-destroying innovation leads to a shift in the technological paradigm, leading to a renewal of the evolutionary cycle (Duysters, 1996). This review of Duysters' hypotheses is relevant in the discussion of the unmanned systems industry.

3. Dominant Design

In almost all S-curve evolutionary periods, a dominant design eventually emerges. Argyres, Bigelow, and Nickerson (2011) described dominant design as “a new design that combines product elements in a novel way that immediately sparks a surge in unanticipated demand for that product” (p. 3). The key to this description is the word *demand*, which implies that the product is desired by the marketplace, so much so that competing products must scramble to adapt. There are several strategic responses to a dominant design, including imitation or exit.

Once a dominant design has been established, the technology S-curve might begin to shallow out, as incremental innovation seeks to improve the design. Utterback (1996) warned that “incremental innovation ... is a wise path of least resistance for the established firm, but sustained success in this form of innovation forms a trap for management” (p. 225). He stated, “When radical innovation is plausible... constant incremental innovation can create myopia in the ranks of top management” (p. 225).

Utterback (1996) conducted a study of technological innovation in 41 industries and described three characteristics of an innovation. The first characteristic pertains to an assembled product, not an individual component. The second characteristic is that the new innovation expands demand in the industry. The third characteristic is that the product destroys the competency of existing competitors, thus shifting the technology S-curve. The findings are displayed in Figure 4.

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Characteristics of the Innovation	Source of Innovation (N = 41 industries)		
	Number of characteristics displayed at left	Prime	Non-prime
• Assembled product	0	7	0
• Product expands demand	1	6	6
• Product destroys competency of existing competitors	2	1	16
	3	0	5

Figure 4. Sources of Breakthrough Innovation (from Birkler et al., 2003)

According to Utterback's (1994) research, non-prime participants overwhelmingly supplied the breakthrough innovations that shifted industry S-curves. Utterback's research shows the importance of maintaining a healthy industrial base that is capable of dynamic innovation. This entails maintaining the capability to recognize, foster, and exploit technological innovations from outside the prime contractor base. Utterback and Murray (1977) also acknowledged the greater incentive for small firms to innovate, since initial sales of a new product affect the company to a greater extent than they would a large firm.

4. User-driven Innovation

Determining what drives innovation is another useful starting point for discussion. Von Hippel (2005) defined *lead user* as follows:

1. [Lead users] are at the leading edge of an important market trend, and so are currently experiencing needs that will later be experienced by many users in that market, and
2. [Lead users] anticipate relatively high benefits from obtaining a solution to their needs, and so may innovate. (p. 22)

Von Hippel (2005) stated that most product innovations come from those with lead user characteristics. His theory is based on the assumption that a lead user's innovation was useful to him or her, so it must then be useful to many. This theory has important applications to the discussion of procurement time frames. The DoD procurement time frame is notoriously long, often with years in between technology demonstrations and actual fielding of equipment. A greatly accelerated procurement process could result in an end product more closely aligned with a warfighter's needs.

5. How does the Government Assess Technology Maturity?

The Assistant Secretary of Defense for Research and Engineering (ASD[R&E]) publishes a Technology Readiness Assessment (TRA) guidebook to assist in the classification of technological maturity. The format used today to classify technological readiness was created by NASA and serves as a risk management tool for program managers. A Technology Readiness Level (TRL) between one and nine is assigned to all critical technologies, with level one being the lowest level of technology readiness (Assistant Secretary of Defense for Research and Engineering [ASD(R&E)], 2011). The list of TRLs, their description, and brief discussions of each can be found in Appendix A of this report.

The program manager (PM) is responsible for planning and conducting the TRA, usually after Milestone A. The TRA should be finalized at least 30 days prior to Milestone B. The PM is responsible for assembling a team of subject matter experts (SMEs) knowledgeable in the field for the assessment. Although there is an established procedure for conducting TRAs, in reality they begin well before Milestone A, during the Material Solution Analysis (MSA) phase. The declaration of a capability need in the Initial Capabilities Document begins the entire process of identifying relevant technologies and assessing their maturity (ASD[R&E], 2011). It is important to note that

the assessment of the technology maturity is not just the SME panel's knowledge of the technological state of the art, but its prediction of what the future holds for that technology.

6. Some Government Barriers to Innovation

An area of constant concern to the DoD is how the federal procurement process divides the economy into defense and commercial sectors. Alic, Branscomb, Brooks, Carter, and Epstein (1992) noted that this segregation "impedes defense access to state-of-the-art technology in the commercial sector" (p. 134). They credited the government's need to pursue oversight, accountability, and fairness with this division. The Packard Commission pressed for acquisition of commercial off-the-shelf (COTS) technology for cost savings and because the COTS equipment is often more technologically advanced than that developed under the DoD umbrella. The steeper the S-curve of a given technology, the greater the probability of inferiority a weapon system faces by the time it is fielded.

Utterback (1996) highlighted another important barrier to innovation. He cited the logic of discounted cash-flow analysis as a barrier to innovation strategies, stating that the method "favors modest near-term rewards of high probability to extravagant long-term possibilities of high uncertainty" (p. 226). The study of the DoD's cost estimation techniques will not be undertaken in this study but should be considered when evaluating breakthrough technologies.

Alic (2013) pointed to yet another barrier to innovation in the current acquisition system. In a protracted technology development phase of a major acquisition defense program, once "the design takes on more concrete form, it becomes increasingly difficult to revisit the overall concept for reasons including the risk that even the appearance of difficulty or delay could invite political attack" (p. 15). He pointed to the importance of the architecture by emphasizing that once it is defined, "no amount of analysis, modification, and refinement can salvage a difficult concept" (p. 15). This point calls to mind the debacle of the V-22 and JSF procurement processes. The influence of political stakeholders in the procurement process cannot be denied.

C. TECHNOLOGICAL DEVELOPMENT IN THE AVIATION INDUSTRY

The aviation industry provides an excellent platform for evaluation of defense research initiatives, due to the close relationship between the federal government and the industry. It is also easy to draw parallels between the early U.S. fixed-wing industry and today's unmanned systems industry. There are almost 100 years of evolutionary history to guide decision-making in future endeavors.

Lorell (2003) delineated five separate eras in the evolution of the fixed-wing industry. The biplane era was first, followed by the monoplane, the subsonic jet era, the supersonic jet era, and finally the stealth era. The boundaries of these eras cannot be drawn with a fine line. There is always overlap, as the emerging technology competes with the existing technology before it can no longer be denied. In some cases, the overlap does not disappear entirely. The Douglas A-1 Skyraider is an excellent example of this overlap. The Skyraider was originally developed in the 1940s but saw continuous use through the 1980s, well through the subsonic and supersonic jet eras. Although the reciprocating engine design was technologically inferior to the jet engine, the combination of range, durability, and substantial payload made it an ideal close-air support aircraft. Even as the jet age was emerging in the 1950s, A-1 Skyraider designers found ways to eliminate 1,800 pounds of weight from the airframe, increasing the Skyraider's range, speed, and payload capability (Heinemann, 1953).

Using the technology S-curve framework, one could produce graphs depicting the substitution of technologies across the eras. Using a metric of airspeed would result in little overlap of the S-curves between the biplane and supersonic jet eras. However, a payload metric would show significant overlap as each new technological leap struggled in the early stages to overcome aerodynamic limitations on payload. Using a metric of range (flight time between refueling), certain reciprocating engine monoplanes have distinct advantages over turbine-engine supersonic aircraft. This was among the reasons the A-1 Skyraider was able to thrive alongside its more technologically advanced competition.

One way to gauge industry health could be the number of participants in an industry. Lorell (2003) presented a graph of prime contractors in the U.S. fixed-wing aviation industry since its inception. Figure 5 shows the growth of the U.S. fixed-wing aviation industry from 1910 to 2000, with the number of prime contractors on the y-axis. *Fighters (Navy)* refers to fighter aircraft procured only by the Navy. *Fighters (AF + Navy)* refers to fighter aircraft procured jointly by the Navy and Air Force. *Fighters (AF)* refers to fighter aircraft procured only by the Air Force.

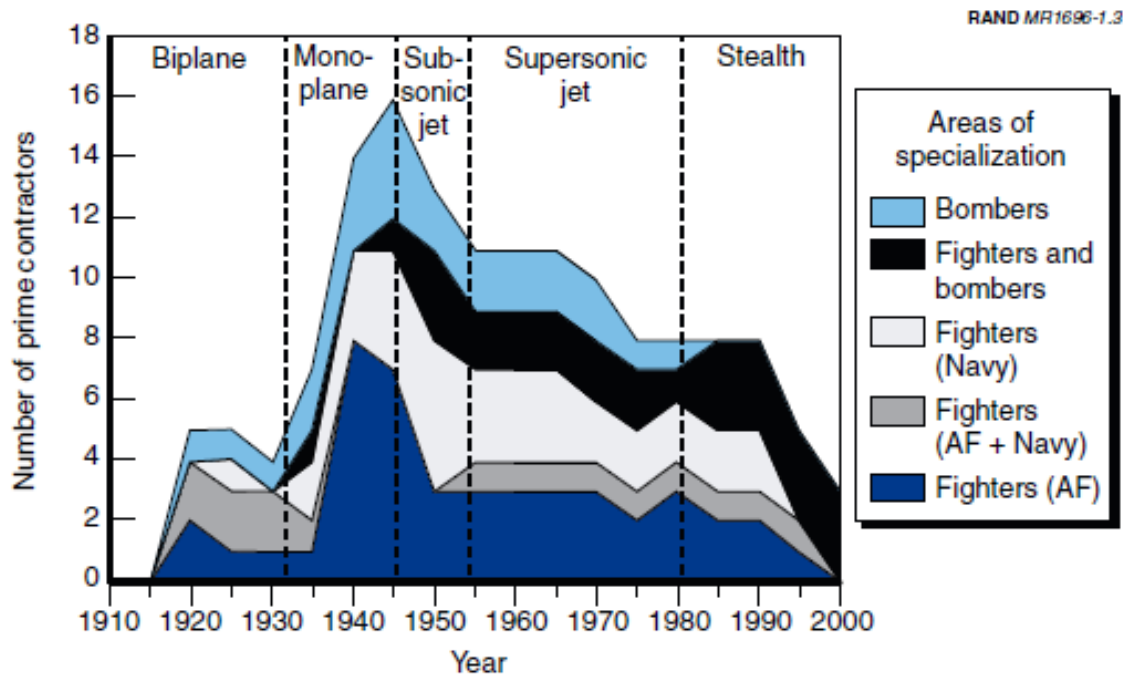


Figure 5. Prime Contractors During Fixed-Wing Aircraft Evolution (from Lorell, 2003)

Although the U.S. gave birth to powered flight, it did not advance the aviation industry as much as other nations leading up to World War I (WWI). In 1913, the U.S. government appropriations to the aviation industry amounted to \$125,000, while the French government appropriated \$7.4 million for aviation (Pattillo, 2000). The most significant display of U.S. government recognition of the importance of aviation was the establishment of the National Advisory Committee of Aeronautics (NACA), an early precursor to NASA, in 1915. The NACA Langley Memorial Aeronautical Laboratory

was established in 1917 and became the world's most advanced aviation test and experimentation facility (Pattillo, 2000). Shortly following the official U.S. declaration of war in 1917, Congress appropriated \$640 million for the purchase of aircraft, which was to date the single largest defense appropriation ever (Pattillo, 2000).

Thus, the first spike in U.S. military aviation occurred in the run-up to WWI, as shown in Figure 6. U.S. military aircraft production exploded 400% in 1917 to a peak production of 14,000 aircraft in 1918 (Lorell, 2003). At this time, the civilian market expressed growing interest. However, following the armistice, U.S. military budget cutbacks crippled the fledgling U.S. industry, resulting in a 90% reduction in funding from 1919 through 1920 (Lorell, 2003). The precipitous decline in procurement hampered innovation and competition for almost a decade, during which time France boasted the world's largest and best air force. Lorell (2003) also pointed out government procurement decisions that further crippled the industry, like separating design and production contracts for a bomber aircraft designed by Glenn L. Martin. Glenn L. Martin won the design contract for a bomber aircraft, but production went to Keystone, which resulted in Martin withdrawing from the bomber market for about a decade. Government contracting decisions like this stifled industry and impeded innovation the entire decade. The decrease in government funding, an immature civilian market, and detrimental government policies resulted in staid, conservative aircraft design and production that set the U.S. industry back immeasurably (Lorell, 2003). The armistice resulted in the cancellation of at least 61,000 aircraft orders and the liquidation of 90% of peak production capacity (Pattillo, 2000).

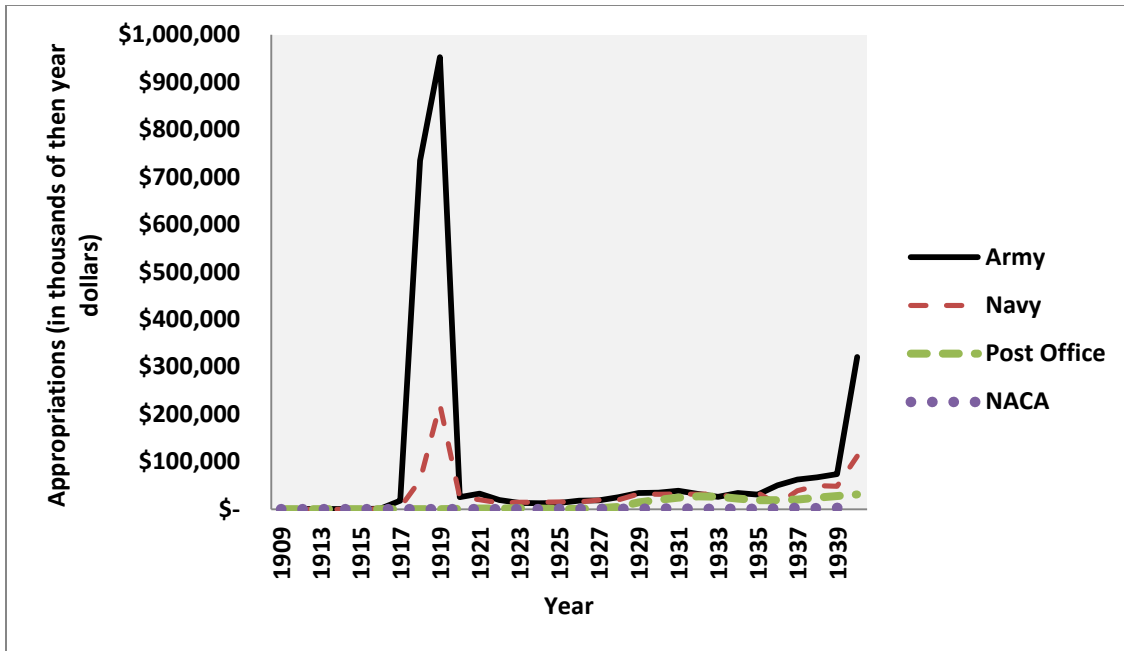


Figure 6. Appropriations to the Fixed-Wing Aviation Industry (after Pattillo, 2000)

The diversity of contractors was also critical to the development of the early aviation industry. As Lorell (2003) noted, while there were five prime aviation contractors at the peak of WWI, there were several smaller companies that made important contributions to aviation technology. Actually, 31 aircraft manufacturers were listed in the 1919 Jane's almanac. Grover Loening's companies never achieved prime status, but early designs resulted in the basis for the M-8, one of America's first fighter planes. The L-W-F Company, founded by Charles Willard in 1915 invented the monocoque fuselage, an innovation that created a new technology S-curve in aircraft design (Pattillo, 2000).

Lorell (2003) identified the end of government subsidies for airmail in 1930 as the trigger for growth in the commercial industry. Airlines realized that to remain profitable, they had to branch out into passenger transport. Despite the lack of government procurement of military aircraft, the commercial industry made strides in building larger, more complex aircraft. Competition spurred innovation, and Lorell (2003) noted the development of stressed skin wings, retractable nose-gear, and lighter, cooler-running engines during this time.

One of the most important developments in the U.S. fixed-wing aviation industry was indicative of the benefits of commercial application (Lorell, 2003). Competition between Boeing and Martin produced a revolutionary new monoplane bomber with the ability to crossover into the commercial market. As Lorell (2003) noted, this dual-use potential was enough to justify the risks taken by the competitors, which resulted in bombers being more technologically advanced than fighter aircraft at that time. The Martin B-10 that won the competition also saw healthy overseas sales, which accounted for more aircraft than purchased by the U.S. government (Lorell, 2003). On the other hand, the lack of commercial appeal in fighter aircraft resulted in the U.S. lagging far behind many countries in fighter development. U.S. fighter production began to pick up once companies realized overseas demand for fighters was rapidly increasing (Lorell, 2003).

NACA proved the effectiveness of government R&D in fixed-wing aviation with advances in naval aircraft during this time. NACA research directly led to the development of streamlined cowlings, aluminum structures designed to resist saltwater corrosion, and engine nacelles integrated into the wing itself, rather than suspended below (Pattillo, 2000). All these developments crossed over to the civilian market as well, propelling further innovation.

The subsonic jet era following World War II (WWII) saw a decrease in the number of prime contractors from 16 to 11, but competition and innovation were high due to the emergence of the revolutionary jet technology (Lorell, 2003). Captured German documents detailing experimentation provided the springboard for some companies to enter the market. Companies began taking more risk, buoyed by increasing government R&D expenditures. In light of the S-curve discussion, it is interesting to note that the first subsonic jet fighters were substantially inferior in many ways to propeller driven aircraft of the era (Lorell, 2003).

As Lorell (2003) noted, the greatest era of innovation in fixed-wing aircraft occurred in the early years of the supersonic jet era. Lorell (2003) stated that the appearance of advanced German research and the surprising capability of the new Soviet MIG jet fighters pushed the U.S. to new heights of R&D. The use of lighter, more durable metals (primarily titanium), radical new design features, and increases in funds

for testing and evaluation resulted in intense competition. During this era, aeronautics was the fastest growing R&D expenditure for the U.S., accounting for over 30% of all aviation industry research funding (Hooks, 1990). Despite its fruitfulness, this period was not without difficulty for firms that withdrew from the industry when risks did not result in long-term procurement contracts.

By the early 1960s, exploration began to decline and exploitation of existing technology increased. Secretary of Defense Robert McNamara changed procurement policies in an attempt to cut unnecessary R&D expenditures. He cut prototype and technology demonstration testing significantly and repurposed proven aircraft like the McDonnell F4H-1 Phantom II for other missions (Lorell, 2003). According to Lorell's (2003) data, there were 122 manned aircraft R&D programs in the 1950s, but only 39 in the 1960s and 1970s combined.

The stealth technology era was also marked by intense competition and innovation, with radical new technologies being developed to limit radar cross section. DARPA played a key role in the development of the revolutionary F-117 stealth aircraft and other low-radar cross section-related technology (Lorell, 2003). Unlike previous eras, stealth technology did not have as much impact on the commercial industry due to the sensitivity and costs associated with the advanced technology. This also limited foreign military sales. However, the F-16 Fighting Falcons developed during this time has seen much success in foreign military sales, with over 24 nations procuring them (Lorell, 2003).

Since the stealth era, the fixed-wing aviation industry has seen a dramatic drop in the number of manned aircraft programs. As a result, there are currently only three prime contractors in the industry, with larger prime contractors like Boeing acquiring historically successful companies like McDonnell-Douglas. The rapidly rising costs of procurement are consuming resources that otherwise could be used for R&D of the next technology.

Now, defense officials are attempting to find the minimum level of activity required to sustain a firm's status as a prime contractor for military aircraft (Birkler et al.,

2003). The eras of greatest innovation in the U.S. fixed-wing aviation were marked with intense competition between several prime contractors. Innovations often came from lower-tier firms striving to create a niche in the industry, and rarely came from the dominant firms (Birkler et al., 2003).

This research identifies two themes of greatest import throughout the evolution of the fixed-wing aviation industry. The greatest periods of innovation and competition were spurred not so much by R&D but by market demand, and by the realization that international competitors had better technology. While supply-side tools like DARPA were partly responsible for much of the development in more sensitive technology, the era of greatest innovation was spurred by the technological crossover between military and civilian applications. This highlights the role that demand-side economics plays in technology development.

The other key theme deals with how the U.S. fell so far behind in aviation technology in the period following WWI up to the early to mid-1930s. The decline in funding happened well before the Great Depression. DoD funding for aviation applications from 1917 to 1927 is shown in Figure 7. The figure shows a dramatic drop in defense procurement following the Treaty of Versailles.

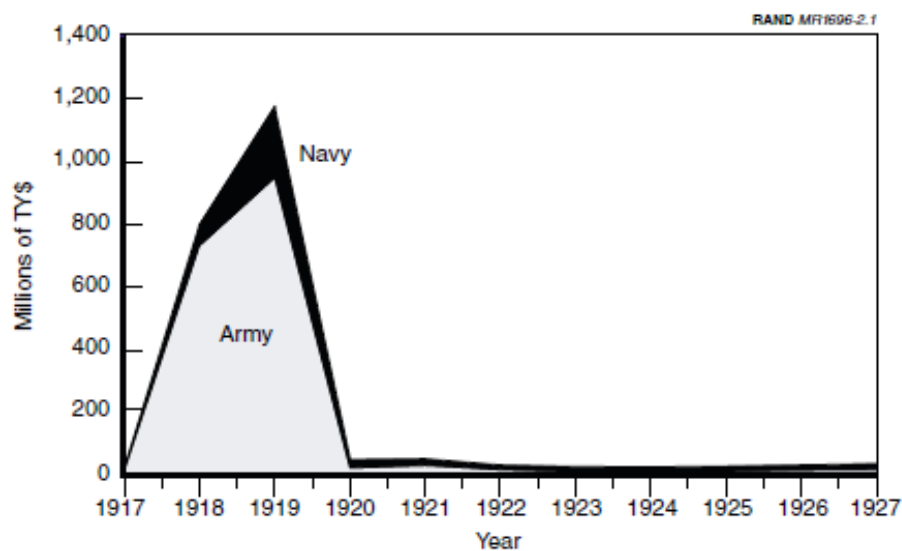


Figure 7. Defense Aviation Appropriations 1917–1927 (from Lorell, 2003)

Figure 8 shows a pronounced gap between the precipitous decline in military aircraft production and the initial growth of the commercial aircraft production. Several factors led to this gap, but it seems that the loss of military aviation funding crippled the fledgling US industry, which relied almost solely on government funding at that time, and did not experience the demand-side pull from the economy that defense leaders expected due to the immaturity of the industry (Lorell, 2003).

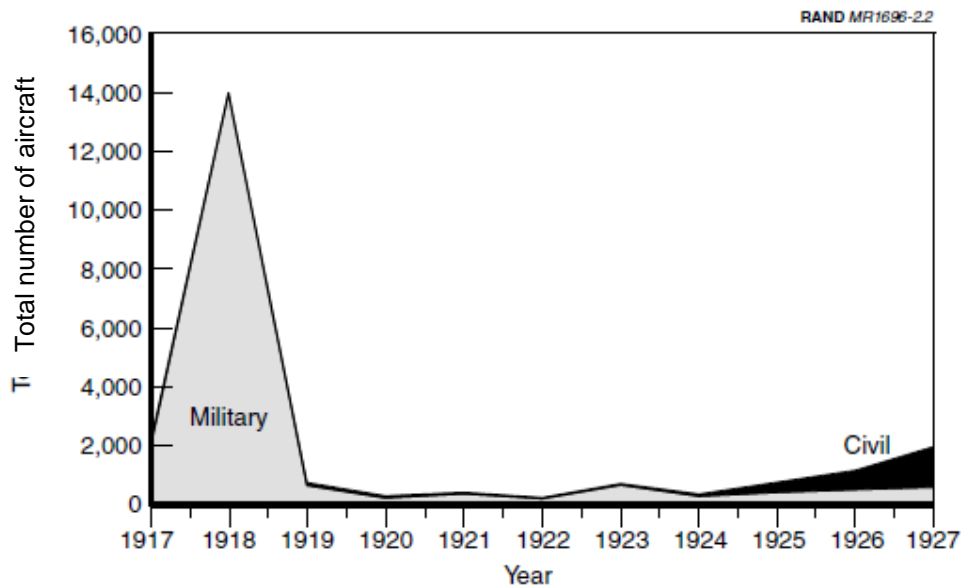


Figure 8. U.S. Military and Civilian Aircraft Production (from Lorell, 2003)

Figure 9 shows aircraft production from 1910 to 1986. There is a pronounced space between the decline of the military industry following WWI and the growth of the civilian industry in the late 1920s. While there is a decline in civilian production following WWII, it recovers quickly with the advent of jet engine and airframe technologies and dominates both aviation industries from that point forward (Pattillo, 2000).

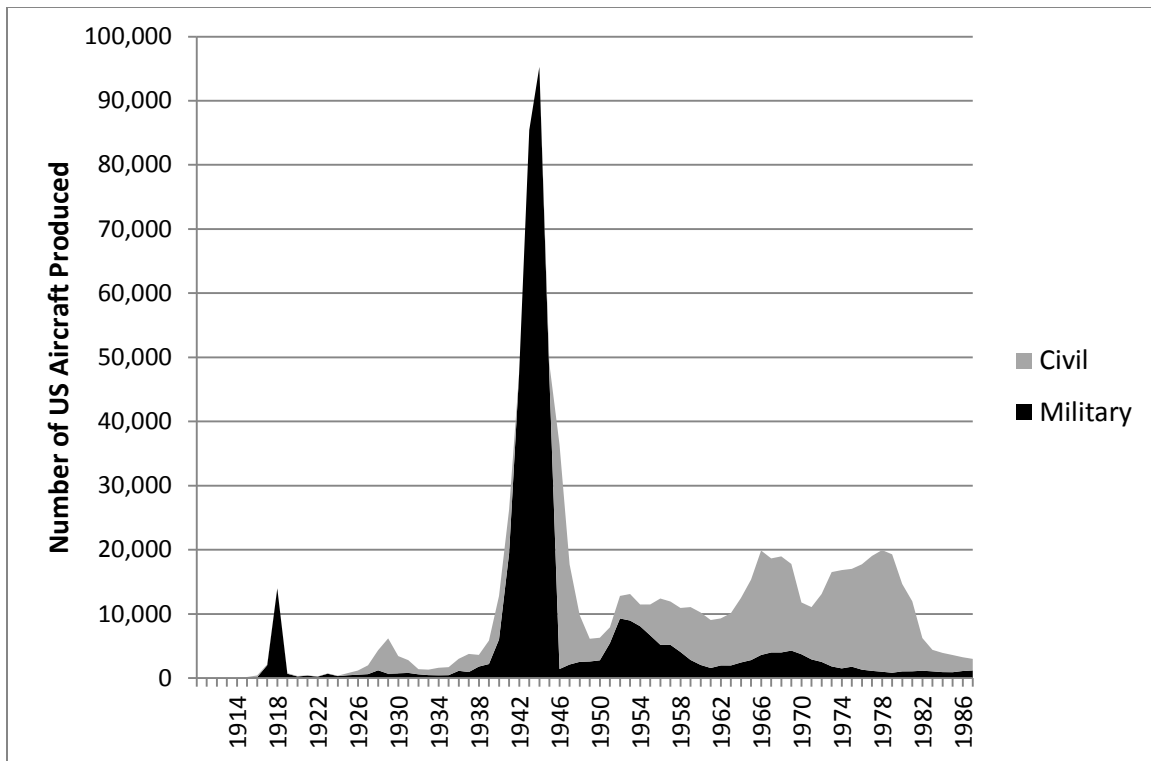


Figure 9. U.S. Aircraft Production 1909–1987 (after Pattillo, 2000)

In hindsight, it is difficult to understand how defense leaders and the U.S. Congress failed to realize the importance of aviation to defense and civilian applications. However, it is important to point out the role government policy played in the development of the U.S. aviation industry in later decades. The repeal of the airmail subsidy to aviation companies precipitated the development of passenger transport aircraft, which more than any other event led to the resurgence of the U.S. aviation industry (Lorell, 2003).

The fixed-wing aviation industry also emphasized the importance of non-prime contractors in technology development and innovation. As stated by Utterback (1996) and others, major innovations rarely come from prime contractors in an industry. Rather, the upstarts usually discover the S-curve shifting breakthroughs. Birkler et al. (2003) applied this principle to major technological breakthroughs in the fixed-wing aviation industry, and the results confirmed it. Their research found that most of the breakthrough innovations in fixed-wing aviation came from non-prime contractors.

In terms of lead user innovation, it seems that eras with the most significant growth benefitted most from lead user input. Early in fixed-wing aviation history, procurement numbers per design were relatively very small, which enabled trial-and-error of end items and subsequent adaption to better suit pilot needs. Fast forward to the current fixed-wing aviation industry, where aircraft are expected to last for decades and often take decades to get from technology demonstration to operational use. Much of the cost overrun in current procurement is directly attributable to extensive airframe modification even after low scale and full scale production has begun. For several airframes, the personnel who initially identified key performance parameters are often retired from the service before the airframe is operationally fielded. While interaction frequently occurs with warfighters during the development and production processes, this interaction often leads to concurrency issues, which bears the majority of blame for cost overruns.

The Performance Based Logistics (PBL) method recently developed in the acquisition field has benefits and drawbacks, but the interaction between the lead user (the warfighter) and the innovative firm is closer than ever. Company representatives work shoulder to shoulder with warfighters around the globe and have the flexibility to innovate on the spot, and outside of normal procurement chains, to deliver what the warfighter needs most.

D. EARLY INFORMATION TECHNOLOGY INDUSTRY EVOLUTION

The history of information technology is very complex; therefore this study will focus on a few key evolutionary developments strongly influenced by the DoD. While DoD involvement in aviation industrial planning presents one extreme, its involvement in other industries is less intrusive, although no less important. However, Utterback and Murray (1977) pointed out that between 1950 and 1970, the largest and fastest growing sectors of the electronics market were defense-related.

This section explores three vignettes in the information technology industry that provide a basis for comparison of the unmanned systems industry: the development of the semiconductor, the experimentation with the VHSIC chip, and the development of RFID technology.

1. The Semiconductor Industry

This section divides the early semiconductor industry history into three periods based on the level of U.S. government intervention.

a. Early Years (1950s and Early 1960s)

Wilson, Ashton, and Egan (1980) recognized three distinct periods in the semiconductor industry. In the first period, the 1950s and early 1960s, the DoD loomed large over both the supply side of R&D funding and the demand side.

Government R&D support was critical during this early era. The Air Force was the single largest contributor to microelectronic R&D during this era, accounting for around 55% of total government R&D for the production of integrated chips (Wilson et al., 1980). Wilson et al. (1980) identified two ways government R&D funding impacted innovation. First, the R&D increased the private company's return to risk ratio, and secondly, the R&D increased riskiness on the part of firms sensing that a technical breakthrough was imminent. Wilson et al. (1980) also pointed out that while a greater percentage of R&D funding went to well-established companies, procurement trended towards newer firms. This was due to the defense contractor's propensity to award R&D to firms with a proven track record, which obviously favored well-established firms (Wilson et al., 1980).

Universities conducting leading edge work also received R&D funding critical to technology advancement (Wilson et al., 1980). The DoD provided \$1 to \$2 million per year to over 100 doctoral candidates studying solid-state electronics in the 1950s, but that research dried up in the 1960s and 1970s (Wilson et al., 1980).

In the microelectronics field, as in the aviation industry, the smaller firms are extremely important in the development of breakthrough innovations. The study of the growth of Silicon Valley confirms this, particularly the proliferation of the so-called Fairchildren and their contributions to innovation. As noted by Hooks (1990), monopoly sector firms supplied only 31% of all semiconductors in 1957, while smaller upstarts like Fairchild, Texas Instruments, Hughes, and Transistron supplied 64%. Due indirectly to Pentagon funding, it was the smaller companies that made the most pronounced

breakthroughs in innovation. In 1954, Texas Instruments, relatively new to the semiconductor industry, invented the first silicon transistor (Wilson et al., 1980). Although the gold-bonded diode was invented by Bell Laboratories, a newcomer named Transistron developed a process for large scale production in the 1950s (Wilson et al., 1980). One defense procurement contract to the new Texas Instruments firm called for “the design, fabrication, and delivery of eighteen different devices in a six-month period” (Wilson et al., 1980, p. 147). Wilson et al. (1980) noted that government R&D and procurement radically cut the time period from invention to commercialization.

In 1959, Texas Instruments invented the integrated circuit. Shortly thereafter, Fairchild refined the integrated circuit and developed a mass-production technique for them (Hooks, 1990). In the early 1960s, a spin-off from Fairchild named General Microelectronics (GMe) made important contributions to the development of metal-oxide semiconductors (MOS), which revolutionized the calculator and computer memory market less than a decade later (Wilson et al., 1980).

Defense programs like the Minuteman 2 intercontinental ballistic missiles (ICBM) and NASA relied heavily on the new integrated circuits. The flexibility of contracting officers during this time facilitated innovative breakthroughs. In an interview with an industry executive, Wilson et al. (1980) pointed to an important vignette:

For example, one firm persuaded the contracting officer to permit it to change from developing an alloy-switching transistor to a germanium-mesa transistor for the Minuteman Missile project. The germanium-mesa transistor proved to be a success that had considerable spillover into the ability to make silicon devices. (p. 147)

It has been estimated that in the early 1960s, the Minuteman II procurement accounted for “60 percent of the total integrated circuit production to that date” (Wilson et al., 1980). Several new and later very successful companies, including Signetics and Advanced Micro Devices (AMD) were begun during this period with strategies centered on the military market (Wilson et al., 1980).

Defense procurement programs significantly accelerated the time to achieve economies of scale (Hooks, 1990). Also, the DoD tended to over-specify products,

choosing performance over cost concerns in most products. This was due to the environmental extremes in which the components needed to operate. This focus on performance instead of cost savings resulted in greatly decreased risk to the companies, which in turn spurred innovation (Hooks, 1990). This over-specification led to greater focus on quality controls in the production process (Wilson et al., 1980).

Before long, companies learned the value of forward pricing, or pricing a product below the current average cost in order to secure a contract, with the knowledge that the increase in production volume would allow the firm to take advantage of learning curve effects (Duysters, 1996). The stability of defense R&D and procurement resulted in a 95% decrease in the cost of a semiconductor chip between 1962 and 1968 (Wilson et al., 1980).

Also in contrast to the aeronautics industry, where few companies fought against advances pushed by the DoD, some firms in the microelectronics industry were hostile to DoD R&D efforts in semiconductor technology, which tended to upset the foundation of the existing, profitable technologies (Hooks, 1990). Hooks (1990) drew a distinction between dominant electronics firms that resisted DoD intervention and smaller, emerging firms that relied more on DoD outlays. The dominant firms at the time (throughout the 1950s and 1960s) included Western Electric, General Electric, RCA, Raytheon, and Westinghouse, among others. The smaller firms included Texas Instruments, Fairchild, and Hughes. The semiconductor research initiated by the DoD, especially the Air Force, saw major breakthroughs come from the smaller firms of the era. Hooks (1990) pointed to the development of the integrated circuit by Texas Instruments and the mass production process developed by Fairchild in 1959. The breakthroughs in semiconductor technology created momentum the commercial marketplace was unable to ignore, which resulted in greater R&D outlays from the larger electronics firms, creating a snowball effect (Hooks, 1990).

Although the DoD had a significant effect on the semiconductor industry during this time, it was not as pronounced as its effect on the aviation industry. As a comparison,

aeronautics programs accounted for 40% of all DoD contracts in the years between the Korean War and the Vietnam War, while electronics programs accounted for less than 13% (Hooks, 1990).

b. Second Period (Early 1960s to Late 1960s)

The second period began in the early 1960s and ended in the late 1960s. This period was referred to by Wilson et al. (1980) as the *laissez-faire* period, where government demand for semiconductors was slowly eclipsed by market demand, which resulted in a relative decrease in government supply-side intervention.

By the late 1960s, the importance of DoD funding of semiconductor exploration began to fade and was replaced and surpassed by commercial R&D expenditures. This transition had two major effects. The increasing importance of commercial funding resulted in a greater focus on cost avoidance (Duysters, 1996). Satisficing took the place of over-specification. This, in turn, forced many smaller competitors out of the industry and forced industry consolidation. By the late 1960s, only five companies dominated the semiconductor industry: Motorola, Signetics, Westinghouse, Fairchild, and Texas Instruments (Duysters, 1996). It is interesting to note that the last two companies benefitted greatly from DoD R&D expenditures early in the integrated chip evolution. Texas Instruments received the majority of Minuteman contracts while Fairchild received the contracts for the Apollo guidance project (Alic et al., 1992).

c. Third Period (Late 1960s to 1970s)

Wilson et al. (1980) described the third period as one of increasing frustration of industry heads with government policy. The increase in government support by foreign countries to their own industry resulted in a power shift in semiconductor production overseas, and U.S. government tax and trade policies were seen as detrimental to domestic industry. This resulted in a “more adversarial tone” (p. 2) between the U.S. government and the semiconductor industry (Wilson et al., 1980).

U.S. trade policy was one of the most contentious topics in the 1970s. Between 1970 and 1975, semiconductor exports grew at an average rate of 17%, but imports

increased an average 45% per year during that time (Wilson et al., 1980). Japanese government trade policy made it difficult for the U.S. to sell semiconductors there, but U.S. policy made it relatively easy for Japanese semiconductors in the U.S.

Despite the difficulties, there were some bright spots in innovation. Wilson et al. (1980) pointed to Intel, a new company in 1970, and the innovation of the Intel 1103 MOS dynamic random access memory chip that created a new S-curve for computer applications. Despite never rising to the ranks of the leading semiconductor manufacturers, RAM products by the company Mostek became the industry standard in the mid-1970s. A new U.S. company named Bowmar built upon the new semiconductor technology and created the world's first pocket calculator, an amazing innovation at the time (Wilson et al., 1980).

These inventions resulted in the rise of entry by new firms. The impetus for the rise in entries was not increased R&D funding by the government, but by obvious and overwhelming consumer demand for products like computers, calculators, and electronic watches. The maturation of the semiconductor industry during this time resulted in increased interoperability of the semiconductor products with a wide range of applications, which meant companies that previously had no stake in semiconductor development were able to procure them and adapt them to their own products (Wilson et al., 1980).

Wilson et al. (1980) emphasized the importance of substantial outside backing to the innovativeness of new firms. Intel's R&D spending in 1970 was only \$1 million, which was small in comparison to the over \$100 million spent on R&D throughout the industry that year. However, Wilson et al. (1980) pointed out that the million dollars was a relatively large sum to the new Intel company and that funding directly resulted in the creation of the 1103 chip.

d. Semiconductor Summary

Figure 10 is a depiction of semiconductor industry entrants on the left vertical axis and approximate industry sales on the right vertical axis. The spikes in industry entry coincide with major milestones in U.S. defense history. The first spike coincides with the

Korean War, as U.S. officials realized that smarter technology was needed to counteract the massive land army strength of the Soviets and the Chinese. The second major spike in entrants occurs in 1959, when the space race with the Soviets began to heat up. The last major spike occurs in the late 1960s, due to increasing commercial demand, but also in response to the increase in hostilities in the Vietnam War and advances in the ICBM programs. It is also important to note that there is an average of five years between spikes in industry entry and spikes in industry shipments, which coincides with the ramp-up time needed by firms to increase production (Wilson et al., 1980).

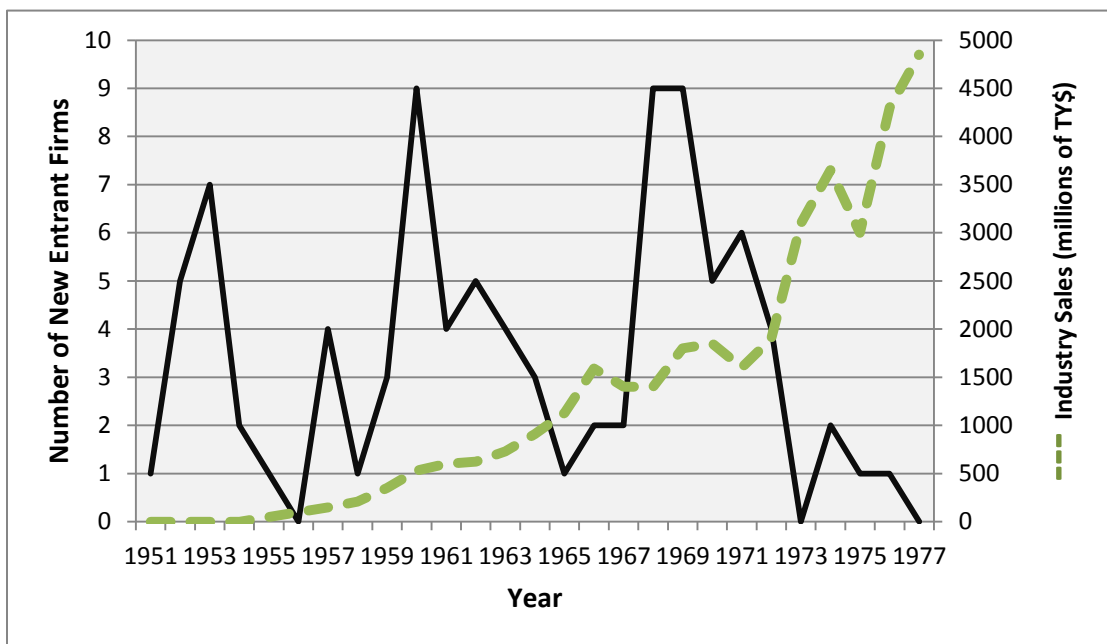


Figure 10. Entrants to the Semiconductor Industry Compared to Industry Growth (after Wilson et al., 1980)

Government funded R&D and procurement provided stability for the fledgling semiconductor industry in a way that is difficult to duplicate. The government began funding solid-state transistor research during WWII, but sales of semiconductors did not show significant growth until the mid to late 1950s. Government supply-side push was critical during this incubation period to sustain the industry until demand-side market forces could find uses for this new technology (Wilson et al., 1980). This incubation period allowed firms to improve production yields without the pressures of the

marketplace threatening their existence. For example, in the early years, finished semiconductors exhibited a high rate of failure during post-production tests. The incubation period helped these companies improve yields on innovative breakthroughs (Wilson et al., 1980).

Wilson et al. (1980), like Utterback (1996), noted that in the past the semiconductor industry conditions favored flexible, innovative firms. However, the late 1960s and 1970s witnessed a drying up of venture capital and the rise of foreign competition as the impetus for more vertical integration by well established firms and fewer new entries, as seen in Figure 10.

Table 1 shows the percent distribution of U.S. semiconductor sales over a 20-year period. The data show the military as the single largest consumer of U.S. semiconductors in 1960, but that percent begins to decline as the commercial market for semiconductors grows. Within 20 years, the military's share of consumption fell from 50% to 10% (Wilson et al., 1980).

Table 1. Percent Distribution of U.S. Semiconductor Sales by End Use
(from Wilson et al., 1980, p. 19)

End Use	1960	1968	1974	1979
Computer	30.0	35.0	28.6	30.0
Consumer	5.0	10.0	23.8	27.5
Military	50.0	35.0	14.3	10.0
Industrial	15.0	20.0	33.3	37.5
Total Value (millions of TY\$)	\$ 560	\$ 1,211	\$ 5,400	\$ 10,500

2. VHSIC Development

In 1977, the U.S. recovered a Soviet sonobuoy and found high-technology integrated circuits copied directly from existing Texas Instruments chips (Naegele, 1989). The U.S. realized that the Soviets were catching up and instituted the Very High Speed

Integrated Circuit Program (VHSIC; Alic et al., 1992). The program ran until 1990 and was one of the highest priority technology programs in the DoD.

As Tsipis and Janeway (1984) described, the 1970s was the era of large-scale integration (LSI), with chips containing more than 1,000 components each. The next goal at the time was very-large-scale integration (VLSI), which could incorporate more than 100,000 components per chip, a hundred-fold increase in performance over LSI. In 1977, the U.S. tasked personnel with forming the VHSIC office to introduce VLSI systems to defense technology (Tsipis & Janeway, 1984). It is important to note that the program did not officially stand up until 1980 and was not fully funded until 1981, during which time the commercial industry had made significant strides toward VLSI technology. Instead of focusing R&D on improving current LSI technology, the program office decided to “leapfrog LSI and go directly to VLSI, realizing that the VHSIC Program would indirectly pull quite a bit of LSI technology into defense systems prior to the availability of VLSI devices” (Tsipis & Janeway, 1984, pp. 36–37). The program office chose to develop VHSIC in the commercial industry, rather than establishing government facilities. At the time, DoD R&D and procurement only counted for 7% of the total U.S. semiconductor market (Tsipis & Janeway, 1984).

The program office took several steps to speed the maturation process of VHSIC chips. In 1984, responding to production delays, the DoD granted a \$102 million subsidy to six contractors to improve pilot production lines in order to increase yield and decrease cost of technically acceptable chips. An additional \$90 million subsidy in 1985 was approved to address equipment-related deficiencies (GAO, 1985).

Although the program led to advances in several microelectronics fields, it fell short of goals sought by the DoD. Alic et al. (1992) stated that the services did not proceed wholeheartedly with the program. The program was originally calculated to cost almost \$1 billion, of which the program office originally estimated the DoD would supply one-third (Tsipis & Janeway, 1984). The final total cost to the DoD was \$918 million (VHSIC Program Office, 1990).

Naegele (1989) pointed to several problems with the VHSIC program. The first major flaw was the inability of the program to get top U.S. chip makers to work closely together. In contracts, the program office inserted a special clause “to license and assist government-designated parties to use contract products for government purposes” (Tsipis & Janeway, 1984, p. 39). This hardly materialized. Although the DoD initially envisioned contracting directly with chip makers, industry leaders recommended systems integrators take the lead, relegating chip makers to subcontractor roles. VHSIC managers saw this as the biggest mistake in the program, since chip makers would have marketed the technology more actively (Naegele, 1989). Instead, systems integrators hoarded information from companies with whom they were in direct competition in other markets (Naegele, 1989).

The second major flaw Naegele (1989) noted was the lack of early technology-insertion initiatives, which resulted in years of delay between development and operational use. In terms of performance, the processing capability of any military weapon system was less than what was available in video games. This increased the calls for program termination, since by the time chips made it into fielded weapons systems they were almost always obsolete in performance (Naegele, 1989).

Despite the problems in the VHSIC program, it created many successes. Arguably, the most important successes came not from the six chip makers that received contracts for VHSIC development, but from the nine chip makers that did not (Naegele, 1989). The DoD call for VHSIC development alerted the entire industry to the potential for new capabilities, which spurred innovation by companies not wanting to be left behind.

Naegele (1989) quoted Bud Kaiser, manager of General Electric’s Microelectronics Center at the time, “The guys who won the contracts were in the catbird seat, because the government paid for their work. They probably would have built those chipsets anyway” (p. 101). Naegele noted that although this was true, the pace at which the technology matured would not have been as quick without the government stimulus. One of the VHSIC program directors estimated that the program put contractors three to

five years ahead of where they would have been without it (Naegele, 1989). Although it was rife with problems, the fruits of this research were on display during Operation Desert Storm.

Instances of friction between military and commercial entities in the production of computer hardware arise throughout the literature. The military's need for over-engineering of computer hardware often results in a product undesirable in the commercial market, mainly due to cost. The need for electronic circuitry to survive environmental extremes does not often result in overwhelming market demand. Another source of friction is the inherent government bureaucracy that almost always delays introduction of new technology. One of the highest priorities in the DoD history, the development of the VHSIC, took over four years from conception to receive full funding (Tsipis & Janeway, 1984). Although the VHSIC made material contributions to the computer industry and shifted S-curves in many areas due to breakthrough technology, the commercial market was able to make significant progress in commercial grade VLSI technology without DoD input.

3. RFID Development

The development and commercialization of the radio frequency identification (RFID) chip also provides a useful basis for comparison. WWII served as the proving ground for RFID technology, when the British placed active transmitters on their aircraft to alert their nation's radar system of their friendly status (Roberti, 2005). Concerted R&D of RFID technology began in the 1950s and was heavily sponsored by the DoD. The Gulf War in the early 1990s resulted in another wave of DoD R&D spending to improve tracking of shipping containers to the Persian Gulf. DoD funding at Pacific Northwest National Labs helped develop micro RFID technology for tracking purposes (Dew, 2006).

The lack of a global RFID standardization system hampered exploitation of the RFID technology. The first system that emerged, Passive Reader Active Tag (PRAT), used an RFID transmitter that carried detailed information about the product, capable of being used by various scanners to transmit product information. This capability increased

the complexity, and therefore the cost of the RFID tag. The other system, which revolutionized the industry, was Active Reader Passive Tag (ARPT). ARPT uses an RFID transmitter that broadcast a single numerical code that would be looked up by an online database for all pertinent information. The drawback was that the scanning computer had to be interoperable with the device to look up the product information, but the upside was that transmitters became much simpler, since they only needed to transmit a numerical code, like a bar code scanner. It was generally assumed there should be one standard for all commercial RFID systems, but firms developing rival system architectures competed over which would dominate the industry (Dew, 2006).

The electronic product code (EPC) numbering scheme used an open-architecture format and an RFID transmitter that broadcast a single numerical code. In the early 2000s, the DoD and Wal-Mart declared for the EPC format and forbade the use of proprietary technology. This joint government/commercial signal for open architecture and non-proprietary technology is solidifying use of the EPC format (Dew, 2006).

4. Information Technology Industry Summary

The research of Wilson et al. (1980) shows that government R&D funds and procurement contracts were critical to innovation in the early years of semiconductor technology. The R&D reduced the technical risk faced by a company, while procurement contracts reduced the company's market risk (Wilson et al., 1980).

In terms of lead user innovation, the companies on the cutting edge of innovation were often the lead users themselves. Many semiconductor companies used the microchips they created in end items also produced by the company. Those that did not use their own microchips were often intimately linked to the recipient, including the DoD. The incredibly fast-paced cycle of technological advancement in the microelectronics field required lead user feedback, lest the end items be rendered obsolete or completely useless before they reached the marketplace.

Utterback and Murray (1977) summed up DoD intervention in the electronics industry by stating that the DoD had an obvious and significant impact on the civilian electronics industry, but not in the way one might think. Up to 1977, no innovations

directly resulted from DoD intervention. And although government procurement has resulted in exponentially larger commercial firm R&D funding, this R&D is mostly spent on “short run problems and improvements and at productivity” (Utterback & Murray, 1977, p. 2). Utterback and Murray (1977) stated the point best:

Defense procurement and spending and sponsorship of R&D have stimulated the civilian electronics industry to introduce new products more rapidly and have led to dramatic increases in the performance and reliability of electronics components and equipment. (p. 28)

In terms of manpower influences in the civilian electronics industry, Utterback and Murray (1977) found that

Defense support of R&D in universities and captive laboratories provided much of the training and many of the skilled human resources needed for the growth of the civilian industry, especially by smaller firms and new entrants. (p. 38)

Utterback and Murray (1977) also discussed the role that other positive government policies, such as second-sourcing and liberal licensing had on the microelectronics industry.

While this discussion by Utterback and Murray (1977) primarily concerned the civilian electronics industry, it has important implications for all industries. Even when government R&D funds are not producing headline-grabbing innovations, they are almost always improving the general knowledge and capacity of the field. Utterback and Murray (1977) pointed to the DoD’s role as information clearinghouses in the dissemination of semiconductor knowledge throughout the industry, which acted as a catalyst for innovation. Holbrook (1995) pointed to a 1952 defense symposium on transistor science, engineering, and manufacturing that spread information on AT&T patents as an important catalyst in the growth of the semiconductor industry.

E. LITERATURE REVIEW CONCLUSIONS

There are several themes that pervade the literature review of the fixed-wing aviation and information technology industries.

- *Point A: Government funding and procurement have been critical in the development of key technologies while serving as an incubator for infant industries*

The contrast between the early fixed-wing aviation industry and the electronics industry is evident. Government funding in the fixed-wing aviation industry directly led to dramatic breakthroughs in technology and innovation. Indeed, many technological advances were applicable only to the government, specifically stealth and weapons employment. In contrast, electronics technology almost never *directly* benefitted from government outlays, but government procurement and R&D were very beneficial to the industry nonetheless. Government outlays were absolutely critical to achieving the U.S. global technological dominance in both industries.

In the fixed-wing aviation industry, government procurement and R&D kept the U.S. at the cutting edge of technology. Government outlays resulted in much innovation. The circa—WWI fixed-wing aviation industry rose and fell with government procurement, crashing as spectacularly as it grew. In contrast, government efforts never directly resulted in cutting-edge technology in the electronics industry. As in the VHSIC case, the DoD product was often technologically obsolete by the time it was fielded, due to more rapid innovation in the civilian marketplace and burdensome, slow DoD acquisition processes.

Government funds were present at the earliest stages of both industries, allowing them to overcome growing pains before the market forces took hold. Here, we see a stark contrast between the industries. The importance of government intervention in the aviation industry is obvious, given the so-called lost decade after WWI where the industry struggled to make gains and actually fell behind other nations. In contrast, the semiconductor industry experienced more even growth. In both cases, government R&D and procurement made up a majority of industry funding in the earliest years.

This study is important to understand the benefits and limitations of government outlays. Government outlays can be extremely beneficial to an industry but are rarely the sole propellant of technological innovation.

- *Point B: However, while important to technological development, government R&D funding has rarely been as important as its procurement decisions (market demand)*

In most research, marketplace demand seems to be the most effective stimulus for innovation. Particularly in the information technology industry, whose leading companies have often been hostile to government intervention, lengthy government procurement processes often resulted in technology that was obsolete by the time it was fielded. With fixed-wing aviation, eras with the most intense competition featured developments that favored civilian applications, such as the end of airmail subsidies and R&D for bomber and transport aircraft in the 1930s.

- *Point C: Major innovative breakthroughs predominantly come from lower-tier contractors and smaller companies*

Historically, major innovative breakthroughs that shift technology S-curves have not come from the leading prime contractors of an industry. In the information technology industry, it can be argued that many of the smaller companies that developed breakthrough innovations were formed with personnel that defected from larger companies. This does not disprove the hypothesis; instead it reinforces the idea that lower restrictions and higher competition experienced by companies struggling to survive and compete compel those companies to take risks that larger companies might not.

- *Point D: Lapses in government attention to areas in both industries resulted in a loss of U.S. global dominance in those areas*

The fixed-wing aviation industry was crippled in the years following WWI, and France quickly became the leading global force in aviation technology due to aggressive procurement and R&D. Government funding was cut before the civilian marketplace was ready to take up the slack. It would take over a decade to get the U.S. fixed-wing aviation industry back on its feet following the Armistice.

Likewise, the recovery of the Soviet sonobuoy in 1977 revealed critical weaknesses in an otherwise dominant U.S. semiconductor industry. The U.S. semiconductor industry has suffered greatly with the rise in production capabilities in east Asia. While many technological breakthroughs still occur on American soil, outsourcing has resulted in a drain of production overseas where tax conditions and labor rates are more favorable.

- *Point E: Flexibility in the procurement process can increase lead user input and result in more rapid fielding of innovative breakthroughs*

As with the Minuteman 2 ICBM example and the early years of aviation, technological advancement often occurs rapidly and must be prepared for despite the limitations of reliable forecasting. An acquisition establishment that values lead user feedback will be better prepared to switch technologies when necessary.

These evolutionary vignettes provide an important framework for the discussion of unmanned systems acquisition. The effect of DoD funds on each industry, especially in the immature eras, can guide acquisition strategy decisions today.

III. METHODOLOGY

I use the comparative analysis methodology to place the current unmanned systems industry in context. I compare today's unmanned systems industry with the early fixed-wing aviation industry and the early information technology industry to draw parallels between prime contractor levels, government policies toward the industries, innovative breakthroughs that propelled the industries, and importance of the technologies to national security.

The conclusion of the Literature Review featured a framework for comparison between the industries:

- *Point A: Government funding and procurement have been critical in the development of key technologies while serving as an incubator for infant industries.*

I examine key technological advancements resulting from government funding in each of the industries. I also quantitatively show an increase in innovation resulting from an increase in government funding and qualitatively analyze historical sources to show that government procurement and R&D ensured the survival and growth of each industry before market forces assumed lead roles.

- *Point B: However, while important to technological development, government R&D funding has rarely been as important as its procurement decisions (market demand).*

I attempt to show quantitatively that market demand and procurement have provided more of an impetus for innovation than government R&D.

- *Point C: Major innovative breakthroughs predominantly come from lower-tier contractors and smaller companies.*

I qualitatively prove that the unmanned systems industry is much like the other industries where the largest companies rarely make the most significant innovations.

- *Point D: Lapses in government attention to areas in both industries resulted in a loss of U.S. global dominance in those areas.*

I qualitatively show how a decrease in government procurement and R&D have led to declines in U.S. dominance in both of the historical industries and how the unmanned systems industry could see similar results, given defense budget cutbacks.

- *Point E: Flexibility in the procurement process can increase lead user input and result in more rapid fielding of innovative breakthroughs.*

I discuss unconventional acquisition practices in all three industries and qualitatively show how unconventional procurement practices have led to increased innovation in all three industries.

The purpose of this comparative analysis is to draw parallels useful for informing an acquisition strategy that will ensure the health of the industry and the U.S. DoD's technological dominance on the battlefield.

IV. STATE OF THE UNMANNED SYSTEMS INDUSTRY

A. INTRODUCTION

In this chapter, I discuss the current state of the U.S. unmanned systems industry, including industry structure, current trends, and forecasts of industry development.

B. A BRIEF HISTORY

Unmanned systems have existed for a long time. However, research still identifies the unmanned systems industry as infant, due to only recent growth in advanced navigation and communications technologies that allow unmanned systems to be operated from greater distances. The maturation of global satellite bandwidth technology made possible the proliferation of systems in the recent wars, from Kosovo to the present day. These developments and the de-classification of advanced technology have led to unprecedented growth and demand (Gertler, 2012).

The U.S. has been developing and procuring unmanned systems for decades, beginning with target drones developed by the Air Force in the 1950s. For decades thereafter, much of the early work on unmanned systems occurred in highly classified programs. Early unmanned systems development was spurred by the shoot-down of Gary Powers' U-2 spy plane in 1960, after which the Air Force approved \$70 million (over \$440 million in FY2013 dollars) for the Red Wagon UAV program. This program was vetoed by the Director of Defense Research & Engineering in favor of manned aircraft and satellite technology (Ehrhard, 2010).

In 1962, Ryan Aeronautical received over one million dollars to develop the Model 147A Fire Fly reconnaissance drone, which performed so well the Air Force ordered seven improved drones at the cost of \$13 million. This contract marked the UAV transition from prototype phase to advanced operational phase. Until the 1980s, UAV programs won a few contracts and made important advancements but could not deliver results like the burgeoning satellite industry, and the DoD terminated each UAV program. Also, in the 1980s and 90s, the Advanced Airborne Reconnaissance System (AARS) program received large sums of money, only to be canceled at the end of the

Cold War due to unprecedented cost overruns and increasing Air Force interest in the B-2 program and satellite technology (Ehrhard, 2010).

As with the other industries studied in this report, innovative breakthroughs have predominantly come from smaller, lower-tier companies. The most famous example is the development of the Predator unmanned aerial vehicle (UAV). One of the most successful unmanned systems in the world, the Predator began in the garage of Abraham Karem, an Israeli-American inventor whose initial design was made of plywood, homemade fiberglass, and a go-kart engine. Karem's design, originally called the Albatross, required only three people to operate. This was drastically fewer than the 30 people required to operate the dominant UAV of that time, the Aquila. DARPA recognized the breakthrough technology and sponsored the development of an upgraded model named Amber. Karem's invention caught the attention (and funding) of DARPA, after which he upgraded the Albatross to the Amber, which cost just \$350,000, less than one hour of flight time for the Aquila ("The Dronefather," 2012).

Despite revolutionizing UAV design and performance, the DoD combined all UAV research into a single program in 1987 and canceled Amber, a move Karem blamed on the largest firms in the industry. Karem's work was sold twice, ending up with General Atomics where it became the Predator, the most recognized and accomplished UAV in the U.S. inventory ("The Dronefather," 2012). Karem had completely broken the mold of UAVs that had until then resembled manned aircraft with no cockpit (Whittle, 2013).

Karem's design team, again with DARPA funding, was also responsible for the A160 Hummingbird, an unmanned helicopter cargo vehicle he developed under his new company, Frontier Systems, which was subsequently sold to Boeing ("The Dronefather," 2012). The A160T version recently competed against the Kaman K-Max for the Marine Corps' unmanned aerial cargo vehicle contract, discussed later in this chapter.

Likewise, a relatively small company, AeroVironment, initiated the small, man-portable UAV revolution with the Pointer, which it sold to the DoD on a small scale before 9/11. The Pointer's worth was proven in Afghanistan immediately following 9/11,

and AeroVironment went from revenues of \$29.4 million in 2001 to revenues of \$300 million a decade later due to multiple small UAV contracts (Finn, 2011).

1. The DARO Experiment

Skeptics sometimes ask why unmanned systems, especially UAVs, are not consolidated under a single service, to minimize duplicative development. This actually occurred in 1993 with the establishment of the Defense Airborne Reconnaissance Office (DARO), which was formed “as both a punishment for the services’ apparent lack of emphasis on this combat support specialty and as a supposed means of achieving greater integration and economy” (Ehrhard, 2010, p. 46). Before DARO’s formation, individual services maintained autonomy in acquisition of weapons systems, much like today. DARO officials felt that “the services had to be marginalized to realize innovation” (Ehrhard, 2010, p. 46).

Ehrhard (2010) pointed to several problems with DARO. First, by consolidating acquisition of all UAV assets into civilian hands, DARO increased inter-service tension, as each service had to turn over all UAV funding to DARO. DARO fought hard for commonality of airframes, searching for a “one-size-fits-all” UAV. This failed on several accounts, most notably because Army and Air Force requirements were very different from Navy and Marine Corps requirements for maritime compatibility (Ehrhard, 2010).

The Lead User discussion is important here. While DARO had no operational control over UAVs, it was responsible for their development, including “sensors, data links, data relays, and ground stations” (Ehrhard, 2010, p. 48). It seems that lead user input was sacrificed at times for commonality and efficiency, which actually stifled innovation during this time. Only one UAV program made it to operational status during the DARO years: the Predator.

DARO only lasted five years. Ehrhard (2010) stated that “DARO extended the general lethargy of U.S. military integration, and in the process, increasingly alienated the services and Congress” (p. 47). This is most surprising considering the technological developments of the 1990s that should have ushered in a golden age, given the

development of GPS, increased computing power, and increased casualty avoidance awareness. Ehrhard (2010) summed up DARO's tenure thus:

After five years of trying UAV innovation by fiat, the UAV acquisition process returned to its natural, if imperfect state. At the beginning, OSD apparatchiks were sure they could break down the barriers to innovation by neutering the service. They suffered from what defense organization historian Paul Hammond called, "the mistaken belief that service interests are not really real, and hence can be overcome by an act of will." (p. 56)

It appears from this examination that consolidation into a single service does not necessarily achieve efficiencies and instead actually stifles innovation and the lead user feedback process that is critical to innovation. Ehrhard (2010) also had several other critical assessments:

The 1990s reinforced an immutable truth concerning weapon system innovation. ... The services, as end users, require substantial autonomy at each stage of the weapons system innovation process. ... [T]he symbiosis between service and machine required for combat innovation depends on the mobilization of an internal constituency. (p. 87)

Also:

The ultimate goal of weapon system innovation is its novel, effective use in combat, and as a byproduct, its enduring integration into a service's support structure. ... The meteoric rise and fall of [DARO] provided strong evidence that "pluralism and untidiness" indeed may be the only way for the U.S. military to achieve weapon system innovation with the UAV. (p. 87)

Much like in the civilian marketplace, the competition between services actually fostered a healthier environment for innovation in the unmanned systems industry. Despite the monopsony condition, the services provided enough of a stimulus to encourage innovation and competition among the small pool of contractors, keeping the industry viable until technology and non-defense market demand caught up.

C. U.S. UNMANNED SYSTEMS INDUSTRY STRUCTURE

As seen in Appendix B, there are more than 31 contractors that supply unmanned systems to the DoD. This is a relatively large number, considering the presence of all three prime contractors (Boeing, Lockheed Martin, and Northrop Grumman) in the

market and their highly popular designs. Since the terrorist attacks of 9/11, the DoD UAV inventory has gone from 167 aircraft to over 11,300 today (*FY2013–2038 Unmanned Systems*, 2013).

Figure 11 shows the number of firms receiving product service code (PSC) 1550 funds per fiscal year. The PSC 1550 is the easiest code to track unmanned obligations, since it is the most distinctly related to unmanned systems. I chose PSC over the North American Industry Classification System (NAICS) because NAICS codes are far more generic, with no code directly targeting unmanned robotics technologies. Several different NAICS codes are used in lieu of PSC 1550 but are also applicable to non-robotics technologies. Although PSC 1550 carries the designation *Drones*, the code is also used at times for unmanned ground and maritime systems. PSC 1550 was first used in 1979. Data are missing for the years 1985 and 1988 in the FPDS-NG database. The distribution reached a high of 44 separate companies in 2011 and has remained at 37 the past two years. Research has shown that high industry participation levels increase competition and the potential for breakthrough innovation.

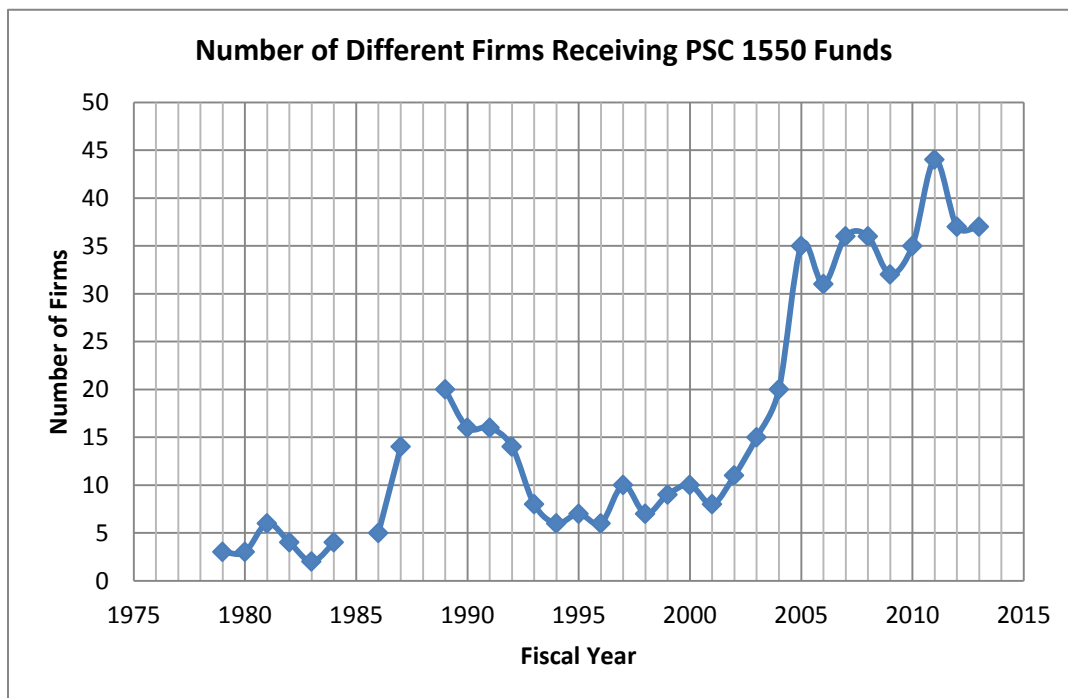


Figure 11. Number of Different Firms Receiving PSC 1550 Funding (after Federal Procurement Data System, 2013)

The chart shows a rapid increase in the number of companies receiving funds leading up to Operation Desert Shield/Desert Storm but shows a marked decline after that conflict. The testing beds of Iraq and Afghanistan led to a dramatic increase in the number of companies following the September 11, 2001 attacks. It is important to note that despite advances in GPS technology and long-range communications, the number of industry participants remained relatively stable throughout the mid- to late-1990s.

D. CURRENT UNMANNED SYSTEMS MARKET TRENDS

Spending on unmanned systems has grown exponentially in the past few decades. The obligations shown in Figure 12 are for PSC 1550 total budget obligations through 2012. The fiscal year (FY) 2013 total as of September 30, 2013, is just over \$920 million, less than half of FY2012 obligations.

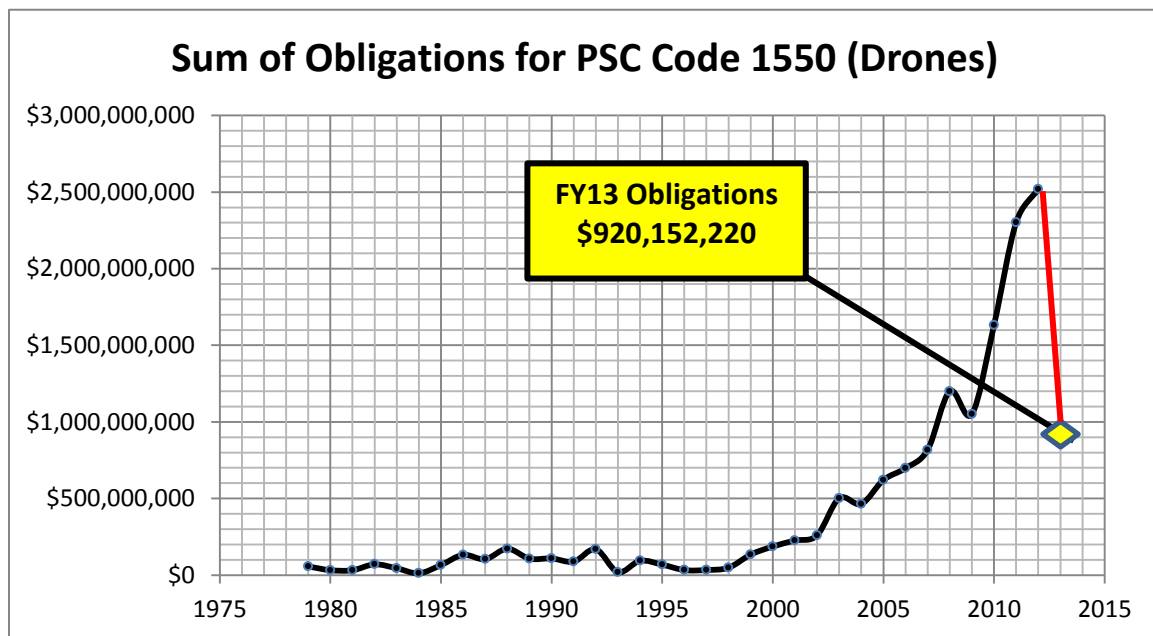


Figure 12. Sum of Defense Obligations for PSC Code 1550 (after Federal Procurement Data System, 2013)

The unmanned systems industry in its current state is flexible and responsive to demand conditions. Sweetman and Eshel (2013) noted that the unmanned aviation system industry is already diverging in response to market demand. The cumbersome truck-

mounted configurations for launching UAVs are already giving way to the smaller man-portable systems or runway-launched aircraft in response to consumer demand. In this case, the consumer, or lead user, is the warfighter. In the current environment of rapid procurement initiatives, the lead user has almost unprecedented access to the ear of the producer, shortening the feedback process and increasing the flexibility of industry to provide a solution to combat needs. By spreading outlays to many contractors, the DoD procurement system has bought the flexibility to experiment in the field and find what works, and most important, what does not work.

In a RAND report on competition and innovation, Drezner (2009) pointed to the unmanned systems industry as an opportunity for innovative competition, citing lower barriers to entry and few truly dominant players as evidence that the industry is primed to grow. This is in contrast to the fixed-wing aviation industry, where more mature technologies and increased focus on airframe commonality leads to less competition and innovation.

Although the U.S. has invested heavily (relative to other nations) in the defense robotics industry in the past two decades, investment in the commercial robotics industry is a fraction of that spent in other developed nations (*Computing Community Consortium*, 2009). The report found one of the most critical bottlenecks is the limited research infrastructure in the U.S. Currently, “many of the proposed efforts, and in particular hardware or software integration efforts, fall outside the scope of existing funding programs” (*Computing Community Consortium*, 2009, p. 59).

1. Unconventional Acquisition Methods

The DoD also benefits from unconventional unmanned systems procurement methods. These methods are getting revolutionary assets to the theater of war in compressed time frames, increasing operational capabilities and preserving human lives. They are also taking advantage of relatively new contractual arrangements that focus more on outcomes, not parts or services.

Arguably the most successful UAV variant to date, the Predator, transitioned straight from the technology demonstration phase to production, effectively bypassing the

development phase. While later on this resulted in having to rework the communications and targeting systems to correct deficiencies, the success enjoyed by this program has been undeniable (GAO, 2009).

The Joint Capabilities Integration Development System (JCIDS) process was implemented in 2003 to assist the Joint Requirements and Oversight Council (JROC) and the Chairman of the Joint Chiefs of Staff (CJCS) in “identifying, assessing, validating, and prioritizing joint military capability requirements” (Chairman of the Joint Chiefs of Staff [CJCS], 2012, p. 1). JCIDS was developed for combatant commanders to identify capability gaps that might not be specific to any one service. The acquisition channels could then address that gap with minimal overlap in development and procurement from competing services (CJCS, 2012). However, there has been much criticism of the JCIDS process, primarily due to its cumbersome and time-consuming response to identified gaps. Some argue that it is difficult to apply the JCIDS process to a specific adversary or environment, since it is inherently forward-looking (Valin, 2008).

Another complaint with the JCIDS process has been the lack of synchronization with the Planning, Programming, Budgeting, and Execution system designed to fund service programs. While the JCIDS process can mandate unified procurement, each individual service approves its own budget, which may or may not prioritize programs the same way. The Government Accountability Office (GAO; 2009) saw this as a stumbling block to greater commonality and efficiency in the procurement process.

The lead user discussion is important in the discussion of the JCIDS process. The JCIDS process identifies the “lead users” as the regional and functional combatant commanders. The intent is for the combatant commanders to provide feedback in the early phases of product development, to ensure that it fills capability gaps (CJCS, 2012). The problem usually lies with the length of the JCIDS process. Procurement schedules for programs can stretch for decades, while combatant commanders and theater requirements frequently change. One must also scrutinize the feedback given by the combatant commanders, since they are rarely actually employing the new product themselves.

The unmanned systems proliferation of the past decade has been successful in large part because it has circumvented the normal time-consuming procurement process. Many of the urgent needs demands have come from those closest to the fight, and it is arguably those lead users who provide the most useful feedback to the producers. Add to that a healthy, commercially viable industry capable of responding to these true lead user demands and it is a powerful asset, although admittedly there will be duplicative development that consumes, but not always *wastes*, resources.

The Joint Urgent Operational Needs (JUON) program was established to respond quickly to capability gaps identified by combatant commanders. The JUON process has a staffing goal of 15 days after the JUON submission, with a complete development and fielding time frame of not more than 24 months (CJCS, 2012). The search for an unmanned cargo aircraft was one such JUON program with positive results. In 2010, the USMC split a \$75 million fixed-price contract award between Boeing and Lockheed Martin to procure an unmanned helicopter capable of external cargo transport, granting \$45.8 million to Lockheed Martin and Kaman, and \$29.2 million to Boeing, for development of the A160T unmanned rotorcraft (Putrich, 2010). The Marine Corps selected the K-Max, and within one year two K-Max unmanned helicopters were in operational use delivering cargo in Afghanistan (Hoffman, 2013). The speed with which the USMC procured and fielded the K-Max is almost unprecedented. The companies involved had been developing the prototypes for years, demonstrating them to the services in years prior. The ability of these companies to conduct R&D and provide functional products immediately demonstrates the benefit of perpetual RDT&E investment.

The use of Performance-Based Logistics (PBL) has been very effective in unmanned aerial systems (UAS) deployment. Under PBL, the DoD pays for “weapons system performance over the entire life cycle of the systems,” (Vitasek, Geary, & Quick, 2006, p. 1) instead of paying for “individual transactions for things like spare parts, repairs, or hours of technical support” (Vitasek et al., 2006, p. 1).

Owings (2010) detailed the success of the PBL practice with the RQ-7B Shadow Tactical UAS. The DoD provides required metrics, and it is up to the contractor to

determine how best to meet them. Although the Army owns the UAS assets, AAI Corporation controls the configurations and is responsible for meeting the metrics. By shifting performance responsibility to the contractor, the DoD can reduce total ownership cost and benefit from contractor measures to improve efficiencies. Owings (2010) discussed the revision of metrics that resulted in a significant reduction in mishaps per 100,000 flight hours, from 450 to 150. The Insitu ScanEagle benefits from similar arrangements, whose contractors are responsible for over 700,000 combat hours, for which the DoD pays an hourly sensor-over-target rate.

These creative arrangements can be mutually beneficial to the DoD and the contractor. Such arrangements can be profitable to the companies, and as Sweetman and Eshel (2013) pointed out, the focus on metrics allows for the unmanned system to be upgraded *outside of conventional acquisition channels* (emphasis added). Innovations can be immediately implemented into the asset as long as the contracted metrics are still met. This flexibility and freedom is not without risk, but the unmanned system industry can take advantage of this procurement program to attain efficiencies while meeting target metrics.

Tadjdeh (2013) pointed to the Army's Rapid Equipping Force (REF) as a model for shortening the lead user feedback loop. The REF was responsible for the procurement of AeroVironment's Puma UAV, which has now become a program of record. The REF communicates directly between the lead user and AeroVironment for upgrades demanded by the warfighter.

Not all rapid acquisition processes have been smooth. The cancellation of the Long Endurance Multi-Intelligence Vehicle (LEMV) in early 2013 marked the end of a difficult and questionable procurement process. Originally designed to cost \$150 million and take 18 months from design to prototype, the process took over two years, and costs ballooned to \$270 million per LEMV. Immediately, the Army had problems with competing contracts, with only two prime contractors, Lockheed Martin and Northrop Grumman submitting bids. When Lockheed Martin realized the development schedule was only 18 months, they withdrew from the competition although they already had invested in blimp research. This left Northrop Grumman as the only competitor.

According to Axe's (2013) research, the Army Intelligence community decided to bypass traditional acquisition channels and went straight to Congress for funding. The LEMV experienced a rash of problems, including schedule overruns, cost overruns, and drastic weight overruns, resulting in an airship that could stay aloft only a fraction of the time it was originally estimated. All these issues combined with the impending budget cuts to doom the LEMV, calling into question the Army Intelligence community's ability to assess TRLs, a process for which much time and effort is dedicated in the acquisition community (Axe, 2013). The LEMV vignette proves the importance of technology readiness assessment. The importance of identifying the maturity of a technology cannot be understated.

Some question why there are so many UAV variants in service. Gertler (2012) summed it up best by emphasizing the role of urgent needs funding, which has allowed combatant commanders to field technology without the drawn-out procurement processes normally encountered. This has drawn complaints from the GAO (2009), which points to concurrent development of similar sensor payloads for Air Force and Army Predator UAVs as a sign of waste. While the GAO takes a pessimistic view towards the alleged overlap, the differing capabilities demanded by each service might in effect be broadening the knowledge base of sensor technology by distributing funds across more companies than if a single sensor was developed by both services. In fact, the components of the Army MQ-1 variant sensor are produced by Raytheon, Northrop Grumman, and Lockheed Martin, whereas the Air Force Variant sensors are produced solely by Raytheon (USD[AT&L], 2012). Gertler (2012) seemed to lament the JUONS process, stating:

Instead of traditional competitions in which systems may be tested against each other in advance of operations, new UAS have been deployed directly to the field, where US forces are able to experiment with and exploit their capabilities. The combination of funding, demand, and technological innovation has resulted in DoD acquiring a multiplicity of systems without significant effort to reduce the number of systems or consolidate functions across services. (p. 6)

Gertler (2012) argued for "centralization of UAS acquisition authority, to ensure unity of effort and inhibit wasteful spending" (p. 10). He also stated "if UAS efforts are too

centralized, some fear that competition and innovation may be repressed” (p. 10). “Some” fear that, because it is exactly what happened in the case of the DARO in the mid-1990s. There is a precedent for acquisition consolidation during combat operations (Kosovo) and during a period of greater technological innovation (GPS, communications, and so on). Gertler (2010) also pointed to a 2005 GAO testimony to the House Armed Services Subcommittee criticizing the DoD for lack of UAV acquisition oversight, which Gertler saw as GAO campaigning for a central acquisition authority. DARO’s short-lived tenure proved that efforts to consolidate at the expense of the services’ needs actually stifle innovation and competition, which could possibly lead to greater costs in the long run.

2. Demand-Side Constraints

While the previous sections have highlighted the more encouraging aspects of the industry, there are several roadblocks to further growth and success in the U.S. robotics industry. Dew (2012) identified five demand-side constraints on the unmanned systems industry that threaten its long-term growth potential.

a. The Perceived Lack of Well-articulated Uses for Robotics Technology

The first is the perceived lack of well-articulated uses for robotics technology. Unmanned systems, specifically unmanned aviation systems, have been the victim of a smear campaign in the media due to reports of drone strikes and an increase in domestic government spying. The DoD is constantly fighting the media war on unmanned systems but must find ways to highlight the technological capabilities that can propel the unmanned systems industry. The success of the Lockheed/Kaman K-MAX unmanned cargo helicopter has greatly appealed to the U.S. parcel service market, and other capabilities, such as 3D mapping, have caught the attention of other civilian agencies and companies (Dew, 2012).

b. Prohibitive Cost of Implementation

Dew’s (2012) second demand-side constraint concerns the prohibitive cost of implementation. In the agriculture industry, where civilian demand for unmanned

systems is forecast to be the greatest (Jenkins & Vasigh, 2013), estimates for the cost of one UAV range from \$10,000 for small UAVs to \$100,000 for the large, 3D mapping UAVs (Caspers-Simmet, 2013), although the article noted that prices are dropping rapidly. An increase in production volume could lead to drastic decreases in price for civilian and military applications alike.

In the DoD, unmanned systems are constantly competing with manned counterparts for funding. Parsons (2013) noted that evolution in maritime unmanned systems has been stunted by the demand for explosive disposal technologies and by the Ohio-class submarine program. This is similar to the rejection of UAVs by the Air Force in the early years of growth. Unmanned systems will always compete against manned systems and other budget priorities for funding.

c. The Risk of Technology Maturity and Unknown Implementation Costs

Dew's (2012) third demand-side constraint addresses the risk of technology immaturity and unknown implementation costs. The DoD has benefitted greatly from the ability to spend money on risky technology. In the fixed-wing aviation industry, R&D outlays on risky technology directly led to breakthroughs in aviation technology, even in the case of stealth and supersonic technology where there was no foreseeable civilian market response to offset the risk. As with the VHSIC study, even though DoD expenditures did not lead to technological breakthroughs in the semiconductor industry, the research resulted in incremental advances that prodded the slumping civilian microelectronics industry to new heights. The DoD has served as a critical incubator of the unmanned systems industry. It is important to note that in some areas such as stealth capability and weapons delivery technology, the DoD will continue to be one of the only customers, regardless of the anticipated increase in market size.

The risk of technology maturity has been highlighted by GAO reports concerned about cost overruns, of which unmanned systems programs have had their share. In a 2006 report, the GAO documented overruns in the Global Hawk and Predator programs. While both programs experienced cost overruns, the differing acquisition strategies of the two programs produced remarkably different results. Between 2001 and 2006, the Global

Hawk experienced development cost overruns of \$1.5 billion (a 166% overrun). The report noted that the Global Hawk sought a “quantum leap in capabilities” (p. 11). The cost overruns were due to “substantial overlap in development, testing, and production” (p. 2), resulting from the high degree of technological immaturity of components. In contrast, the Predator program saw development cost overruns of \$24 million (a 16% overrun) between 2004 and 2006. The incremental approach to development of the Predator, more closely in line with commercial best practices resulted in the improved budget (GAO, 2006).

Although the UAV industry has often been chided for duplicative development efforts, there are several cases that prove the necessity of service-specific requirements. The Navy version of the RQ-4B Global Hawk, the MQ-4C Triton, uses the same airframe but needs drastically different sensor technology to perform its mission. While the Global Hawk is designed to fly at high altitudes over land, the Triton is designed to fly at lower altitudes, where it must consider environmental effects such as icing and wind gusts, and it must stare at a constantly moving sea surface, which necessitates a sensor package capable of picking out every detail against this background. This required several different component (sensor) and architectural (wing and frame) innovations to modify it to naval service (GAO, 2009).

Similarly, the GAO report (2009) pointed to another complaint about the development of separate sensors and flight control systems for the Air Force Predator and Army Gray Eagle UAVs. Although the systems are approximately 80% common, the Army system was designed to be flown by enlisted operators, whereas the Air Force systems are flown by trained pilots (GAO, 2009). While some cases of duplicative development can be called into question, there are many considerations that must be made to future down select efforts that take into account the individual needs of the services. This again points to the importance of lead user feedback and a healthy industry capable of innovation.

Parsons (2013) pointed to a few technological hurdles that must be overcome for demand to increase in the maritime robotics sector. Long-range communications,

improved fuel cell technology, and increased levels of autonomy capable of object avoidance are all noted as areas critical to further development.

d. Unclear Legal and Regulatory Regime Governing Usage

Dew's (2012) fourth demand-side constraint concerns the unclear legal and regulatory regime governing usage. Almost every report on the UAS industry points to Federal Aviation Administration (FAA) UAS regulations as the main roadblock to proliferation. Japan already allows civilian UAS usage for certain applications, and unmanned helicopters are already being used there for pesticide spraying (Harrison, 2013).

Several government policies inhibit the growth of the unmanned systems industry. One agency most often cited as a barrier to growth is the FAA (Harrison, 2013). A 2012 report by the Under Secretary of Defense for Acquisition, Technology, and Logistics on future UAS plans included calls to simplify the FAA Certificate of Waiver or Authorization (COA) process. The FAA, with few exceptions, prohibits civilian UAS operation in the nation's airspace. Presumably, opening up airspace for responsible use of UAS would result in dramatic increases in market demand.

A Congressional Research Service (CRS) report (Harrison, 2013) stated that the primary reason for the strict regulations is the immaturity of the sense, detect, and avoid technology that prevents collisions with other aircraft. This poses a challenge to the industry to innovate in order to thrive. The report also noted government export restrictions as a limiting factor on industry growth, since the Missile Technology Control Regime (MTCR) carries a "strong presumption of denial" (p. 5) for UAS exports (Harrison, 2013).

e. Lack of Competition from Disruptive Innovations

Dew's (2012) fifth and final demand-side constraint involves the lack of competition from disruptive innovations. As many researchers have highlighted (Christensen, 1999; Duysters, 1996; Utterback, 1996), disruptive technologies most often come from firms outside the circle of industry leaders. Throughout history, government

leaders have sought ways to maintain several prime contractors in industries to encourage competition and innovation. In the current fixed-wing military aviation industry, only three prime contractors exist, down from a high of 16 following WWII (Lorell, 2003). One of the greatest periods of aviation industry innovation occurred in the years following WWII, spurred by intense competition and discovery of advanced Luftwaffe designs. As seen in Appendix A, there are currently 31 prime contractors in the DoD unmanned systems industry. Figure 11 shows that there were 37 different companies that received PSC 1550 funds in 2012 for unmanned systems development and procurement. The greater number of competing firms and low barriers to entry make disruptive innovations more likely to occur.

E. FUTURE UNMANNED SYSTEMS MARKET TRENDS

1. Global Growth

Although the R&D spent by the DoD has greatly influenced technological breakthroughs in the robotics industry, many researchers have identified the importance of market influence on innovation. Dew (2012) noted that the DoD needs “to be more explicit about the contributions of demand-side strategies toward military efficiency and effectiveness, that is, toward the DoD’s explicit security goals” (p. 53). The U.S. unmanned systems industry is uniquely poised to take advantage of increased market demand, since the technology is already proven and employed around the globe.

DoD leaders are optimistic about maritime unmanned systems, although they often do not garner the recognition received by UAVs. Insinna (2013) noted that Lockheed is currently contracted for an unmanned underwater vehicle (UUV) that tows mine-hunting sonar equipment. These UUVs will replace MH-60 helicopters designed to tow sonar equipment from the air, resulting in greater cost effectiveness and less danger to humans. Another unmanned surface vehicle will mimic the acoustic properties of large ships. The Navy is depending on advances in autonomy technologies to make these unmanned systems possible. Hull space is a consideration in autonomy evolution, since autonomy requires greater computing power, which in turn requires more space (Parsons, 2013).

Parsons (2013) noted that spending on maritime robots is about 8% of that spent on UAVs. He stated that the reliance on commercial off-the-shelf products has driven maritime robot costs down.

The Association for Unmanned Vehicle Systems International (AUVSI) is optimistic about the economic benefits of unmanned aircraft integration. According to a report by Jenkins & Vasigh (2013), government deregulation of airspace would result in an economic impact of \$13.6 billion in the first three years. The report stated that the agriculture industry and public safety departments would account for approximately 90% of this growth, with the agriculture industry accounting for 80% of the total growth alone (see Figure 13). Tadjdeh (2013) also noted the potential for growth in the subterranean exploration market.

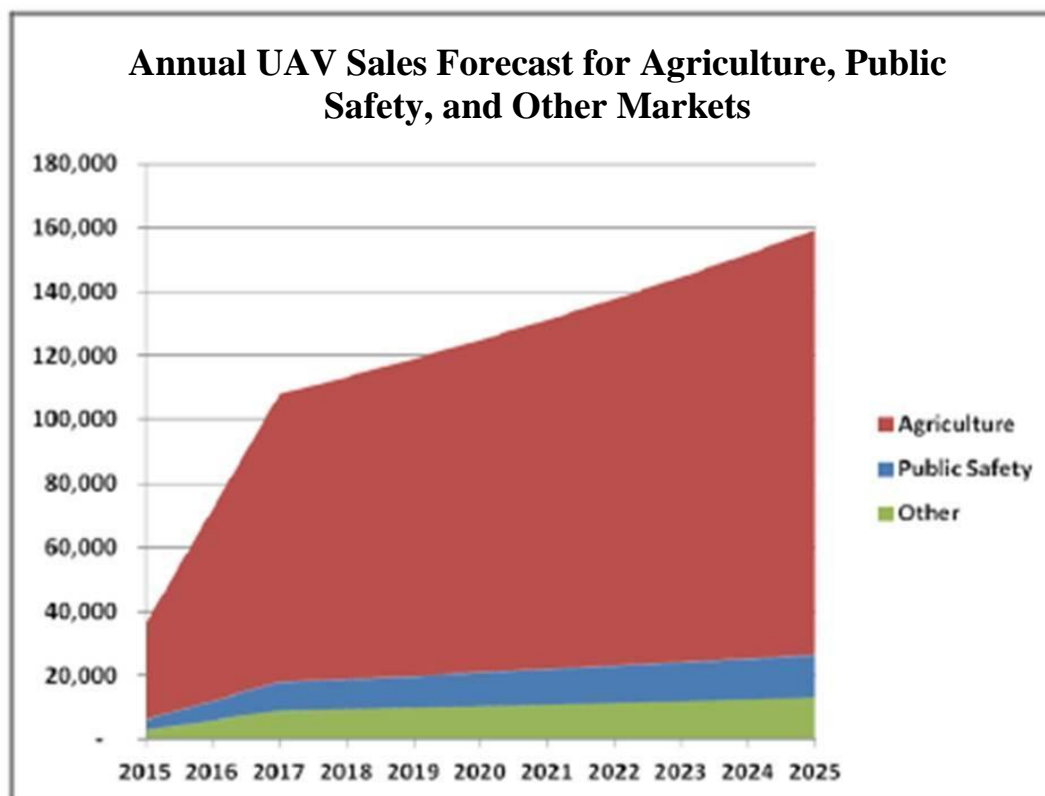


Figure 13. UAV Sales Forecast through 2025 (from Jenkins & Vasigh, 2013)

Jenkins and Vasigh (2013) pointed out other market areas where UAS demand will be highest, such as disaster management, weather monitoring, and freight transport

among others. They stated that there are currently over 100 different suppliers for UAS parts despite the federal restrictions, which portends a viable, competitive marketplace. Jenkins and Vasigh identified conditions upon which their forecast depends, including liability insurance. Their report estimates that every year the FAA delays integration of UAS into the national airspace costs the economy \$10 billion in lost revenues.

A study conducted by the Teal Group (Zaloga, Rockwell, & Finnegan, 2012) also provided an optimistic view of military budget growth for UAS RDT&E and procurement. The report estimated global spending on UAS RDT&E and procurement through FY2022 to reach \$89.1 billion. The report estimates U.S. outlays will comprise 62% of the entire global RDT&E expenditures, and 55% of global procurement expenditures during that time (see Figure 14). Figure 15, another graph from the Teal Group (Zaloga et al., 2012) shows the contribution of each global region to the total value of global UAS production, military and civilian. The U.S. is forecasted to provide the vast majority of production value, with the Asia-Pacific region also experiencing significant growth.

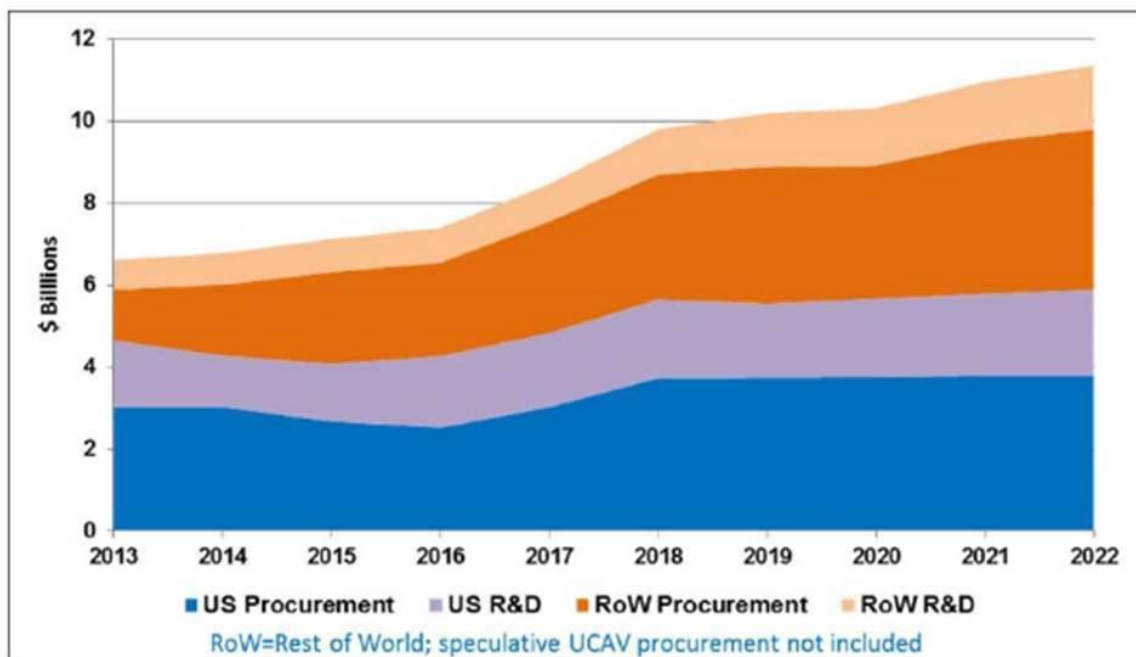


Figure 14. Global Military UAS Budget Forecast—R&D and Procurement (from Zaloga et al., 2012)

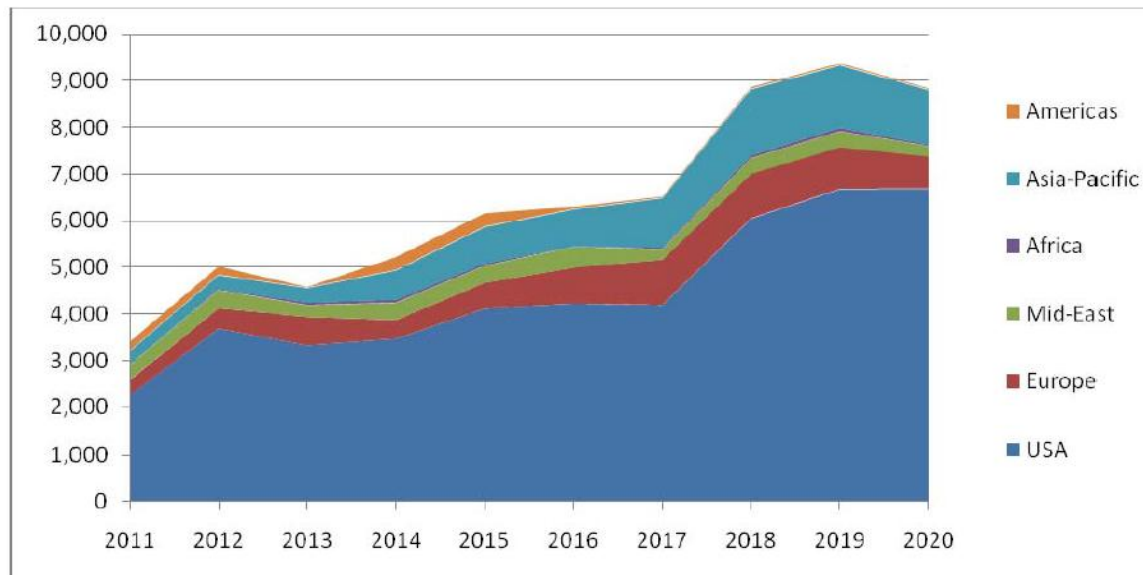


Figure 15. Global UAS Production Forecast: Contribution of Each Region to Total Value (Value, \$ Millions) (from Zaloga et al., 2012)

The Department of Homeland Security (DHS) also stands to benefit from market growth in the unmanned systems industry. Like the DoD, the DHS operates in the air, on land, and at sea. The DHS UAS program flew a record 5,700 hours in FY2012 (Department of Homeland Security [DHS], 2012) and has spent \$201.9 million on UAS since FY2006. This total is 15% of the total DHS expenditures on aviation systems during that time frame. DHS envisions the development of smartphone control of UAS for use in emergency response that could improve real-time damage information gathering (DHS, 2013).

Other countries are already investing heavily in robotics technology. China's recent five-year plan established funding for robotics industrial complexes in five new geographical areas. Each geographical area expects \$8 billion in incentive funding by 2017 (Tobe, 2013).

Tadjdeh (2013) quoted a senior defense analyst in the prospects of small-UAV growth. Despite the past decade of developments, further evolution of small UAVs will be slow. Environmental effects such as wind and poor weather cause havoc on UAV

operations and provide opportunities for breakthrough innovations. The analyst estimates these roadblocks will “take another decade for the rough spots to be smoothed out and real innovation to occur” (p. 1).

Likewise, the Navy is currently developing heavyweight class UUVs, awarding a contract of \$8.4 million to procure large UUVs capable of carrying almost any payload (Parsons, 2013). Increasing attention has been paid to interoperability of unmanned systems, with particular focus on interoperability with NATO allies (Tadjdeh, 2013).

2. Competitor Analysis

Due to focused development efforts, the U.S. has a lead in unmanned systems technology and production. However, other countries have taken note and are beginning to grow their own industries. Of note are China and Russia, who, behind the U.S. rank second and third respectively in total annual defense spending. There are very few public records of funding levels to Russian and Chinese unmanned systems industry participants; therefore it is difficult to make direct comparisons to the U.S. industry. However, there is anecdotal evidence that suggests that the U.S. unmanned systems technological dominance could be challenged in the near future.

Several recent news reports detail Russian efforts to grow their unmanned systems industry. The former commander in chief of Russia’s air forces recently announced that design work had begun on a sixth generation unmanned aircraft, although experts admit that it will not be ready for at least 15 years (Litovkin, 2013). Russian navy officials have plans to incorporate unmanned submarines and sea robotized systems beyond 2020 (Litovkin, 2013). Government-funded activities such as the Central Research Institute of Robotics and Technical Cybernetics (RTC) in Saint Petersburg, the Saint Petersburg Special Technology Center, and the Robot Equipment Laboratory are beginning development on comparable unmanned systems with an eye to the civilian market (Kislyakov, 2013). Established Russian aviation companies like Kamov and Sukhoi are developing unmanned rotorcraft and fixed-wing aircraft, respectively (Fedutinov, 2013). Russian and United Arab Emirate defense contractors are also teaming up to develop an unmanned combat helicopter (Rapoza, 2013).

China's advances in robotics technologies are a greater concern to many (Moss, 2013). A U.S.-China Economic and Security Review Commission report (Hsu, 2013) on China's UAV industry detailed several government enterprises tasked with unmanned systems development. These universities and research facilities are receiving government funding increases for unmanned system development.

China has three main R&D centers with university affiliations. The Beijing University of Aeronautics and Astronautics is China's leading aeronautical university and receives state funds to advance R&D in marketable technologies. Nanjing University for Aeronautics and Astronautics receives state funds for R&D in cutting-edge technologies and has reportedly created China's first unmanned rotorcraft and high-altitude UAV. Northwest Polytechnic University hosts the Xi'an ASN Technology Group, which is China's largest UAV production company and R&D base. Its primary customer is the People's Liberation Army (Hsu, 2013).

Already, some predict a drone race between the U.S. and China. The Defense Science Board task force report (2012) on unmanned autonomy specifically mentioned China's progress several times and cited its rise as "worrisome" (p. 69):

In a worrisome trend, China has ramped up research in recent years faster than any other country. It displayed its first unmanned system model at the Zhuhai air show five years ago, and now every major manufacturer for the Chinese military has a research center devoted to unmanned systems. (p. 69)

Although the report acknowledged the lack of funding data for Chinese unmanned systems development, it pointed out that unlike the U.S., China has no export restrictions on its unmanned systems. Although China lags behind technological development in the U.S. and Europe,

the military significance of China's move into unmanned systems is alarming. The country has a great deal of technology, seemingly unlimited resources and clearly is leveraging all available information on Western unmanned systems development. China might easily match or outpace U.S. spending on unmanned systems, rapidly close the technology gaps and become a formidable global competitor in unmanned systems. (p. 71)

Perhaps the most alarming information to come from China's drone program is the much lower price tag on seemingly comparable UAV variants. The Chinese equivalent of the Reaper UAV is estimated to be significantly cheaper than its U.S. counterpart, although a comparison of capabilities is unknown. The prospect of cheaper drones and the lack of Chinese export restrictions have attracted some African and Asian nations to the Chinese industry (Zhou, 2012). China is already using UAVs for border reconnaissance along the North Korean and Myanmar borders (Moss, 2013).

China is currently developing drones to rival every class of U.S. drone, with prototypes resembling the most advanced U.S. UAVs on display at trade shows and military exercises (Moss, 2013). The China Aerospace Science and Industry Corporation (CASIC) is China's largest producer of non-military drones, and it expects to see government orders double in the next year due to East China Sea island sovereignty disputes (Denslow, 2012).

The Defense Science Board Report is seen as unnecessarily alarmist by some (Moss, 2013), but the message is clear. The technology gap between the U.S. and rival nations is not as distinct as perhaps it once was and could be rapidly closed given the mix of policy and market issues that threaten the U.S. industry. What is more concerning is "the proliferation to the developing world of armed, unmanned systems that China's low prices, and even lower export barriers, may soon begin to drive" (Moss, 2013, p. 3).

Hsu (2013) pointed to three factors that will facilitate growth in China's unmanned systems industry. The first is the fact that the People's Liberation Army controls a large majority of China's airspace, which provides abundant testing grounds for both military and civil UAVs. The second factor is China's growing satellite constellation, designed as an alternative to the U.S. GPS constellation. Hsu's (2013) third factor is maturation of Chinese support services for UAV employment, especially robotics programs like flight control systems and data recycling programs.

The U.S. has greatly benefitted from the wars in Iraq and Afghanistan, where focused development efforts and close interaction between user and producers has advanced the state of the art farther than ever. This has been the U.S.'s chief advantage

over rival nations. However, the drawdown of combat forces in Afghanistan will minimize this focused development to an extent. The U.S. will still employ unmanned systems in the war on global terrorism, but the feedback loop will not be as compact as it is at the moment. The U.S. will no longer enjoy this advantage over rival nations, which will facilitate closing the technological gap.

Without adequate public budget records, it is difficult to gauge the maturity of our rivals' unmanned systems industries. At the moment, it seems as though U.S. investment in unmanned systems development is the highest of all nations. However, the amount of funding is sometimes not as important as other factors. Current government policies could irreparably harm U.S. efforts to maintain unmanned systems dominance.

F. CONCLUSION

We are living in what some might call a golden age of unmanned systems technologies. With the advent of several critical complementary technologies, the industry is poised to grow significantly. Despite the favorable reports of combat performance over the past decade, though, there is still much work to be done in many technological areas to continue advancing unmanned systems. Other nations have indicated their desire to pursue unmanned systems technologies. Despite enjoying a commanding lead in unmanned system development, the U.S. is at risk of losing its dominance in the long run.

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V. COMPARING THE UNMANNED SYSTEMS INDUSTRY WITH THE EARLY FIXED-WING AVIATION INDUSTRY AND INFORMATION TECHNOLOGY INDUSTRY

The purpose of this comparative analysis is to draw parallels useful for informing an acquisition strategy that will ensure the health of the industry and the DoD's technological dominance on the battlefield. The unmanned systems industry is very similar to the early fixed-wing aviation and microelectronics industries on many levels and can provide an important comparison for what policy decisions the DoD must execute to avoid mistakes in the U.S. robotics industry. Historical study shows that these industries complement, supplement, and reinforce one another and can serve as a blueprint for policy decisions in the unmanned systems industry.

For this comparative analysis, I use the themes discussed in the literature review conclusion to compare and contrast each of the historical industry examples with the unmanned systems industry. Using these themes, I point out where government intervention helped or harmed the early industries, and how similar policies might affect the future of the unmanned systems industry.

1 Point A: Government funding and procurement has been critical in the development of key technologies while serving as an incubator for infant industries

This point requires some clarification. While defense unmanned systems applications make up a portion of the U.S. robotics industry output, U.S. robotic technology has a strong presence in the manufacturing industry. The robotics industry has also thrived overseas in manufacturing applications. However, this research focuses on the segment of the robotics industry applicable to defense, which has recently benefitted from advances in miniaturization, communications, and navigation.

There are many parallels between the early years of the three industries. In all three cases, the earliest market was almost exclusively defense-related. Although there were many failures, defense funding resulted in global technological dominance of all three industries at some point in their evolution.

The current unmanned systems industry is remarkably similar to the early fixed-wing aviation industry around WWI. Hostilities overseas created a burgeoning defense demand for both industries. In the fixed-wing aviation industry, civilian aircraft production was almost nonexistent until 1924. Figure 8 shows that for the first 10 years of the industry, production was almost completely limited to military programs (Pattillo, 2000). Pattillo (2000) quoted Major General William Lassiter on the aviation industry in the 1920s:

[The aircraft industry] depends for its existence almost wholly upon orders placed by governmental services. ... The development of commercial aviation will stimulate the aircraft industry, but orders from the military services must be depended upon, at least for the immediate future, if the industry is to be kept alive. (p. 57)

The government kept the aviation industry alive but misjudged its importance and learned an important lesson when it prematurely withdrew funding before the commercial market matured. The decline in the U.S. aviation industry's global standing proved the importance of government funding to the nascent industry.

Likewise, in the microelectronics industry, it is important to note the time span between the invention of computing devices and commercial proliferation. Table 1 shows that the defense market for semiconductor sales comprised over 50% of the entire U.S. market in 1960 (Wilson et al., 1980). This monopsony situation often resulted in over-specification of products, which advanced the microelectronics industry more than it would have in a satisficing market situation. As Utterback (1977) pointed out, between 1950 and 1970, the largest and fastest growing sectors of the electronics market were defense related.

As with the fixed-wing aviation industry in the 1930s, the unmanned systems industry is just now eyeing unprecedented global market demand after decades of development. The high cost of operation in the early decades, combined with limited passenger payloads, ensured that fixed-wing aviation made little headway in the commercial marketplace. Likewise, the microelectronics industry was almost exclusively defense related in the initial years. The unmanned systems industry has followed this trend. The reasons for exclusivity differ somewhat, but the high cost of end items initially

kept manned aircraft, microelectronics, and unmanned systems out of the commercial marketplace for years. Just as the increase in fixed-wing aircraft payload led to the ability to carry more passengers, thereby making it more cost effective, the increase in UAV payload has made it more cost effective for commercial applications. Just as the decrease in microelectronic prices led to a dramatic increase in market demand, the decrease in the price of unmanned systems has put it on the brink of significant growth. However, until this commercial demand materialized in each industry, the U.S. government was the primary force behind technology evolution in both requirements definition and funding.

2. *Point B: While important to technological development, government R&D funding has rarely been as important as market demand*

In all defense industries, increases in R&D usually occur in concert with increases in procurement. With increases in wartime appropriations, the U.S. increases its defense budgets, which usually increases both R&D and procurement. It is difficult to break out R&D and procurement data in the two historical industries, particularly due to the lack of adequate historical funding detail. It is also difficult to break R&D data out from procurement data in the recent unmanned systems data, since the individual program funding detail combines the two categories. However, the levels of defense procurement vice commercial procurement can be used to estimate the market demand influences in each industry.

In the fixed-wing aviation industry, the periods of greatest innovation came during periods of conflict. While the defense department maintained R&D funding to the industry almost non-stop throughout its history, the periods of greatest innovation came during the largest procurement cycles. The period of greatest fixed-wing aviation innovation occurred in the 1940s and 1950s as WWII and the Cold War resulted in the most significant spikes in defense procurement.

Likewise, in the microelectronics industry, R&D played an important role in promoting risk-taking by firms sensing that a technical breakthrough was imminent. As Wilson et al. (1980) noted, although larger companies received a majority of government R&D funds, smaller companies typically received more procurement contracts.

Regulations that governed R&D outlays favored established firms with a proven track record, but these regulations did not extend to procurement, where the government was allowed to get the best equipment for the job (Wilson et al., 1980). The increase in procurement funding to smaller companies increased the probability of breakthrough innovation.

As in the VHSIC study, government R&D designed to leapfrog existing and forecasted technologies did not lead to the result desired by the government (Naegele, 1989). It was commercial demand spurred by the prospects of advanced computing and the challenge of staying ahead that led to the most significant developments. The commercial market was able to outpace government R&D, as some companies' survival was dependent on remaining at the cutting edge of technology. Likewise, although the DoD first argued for non-proprietary technology in RFID systems, it was demand from the commercial sector, particularly Walmart, which began the standardization process (Dew, 2006).

The single biggest impetus for civilian demand in the fixed-wing aviation industry was the repeal of government subsidies for airmail in 1930 that pushed firms into passenger transport as a way to increase revenues (Lorell, 2003). The commercial focus on larger transport aircraft led to a new era of design that had significant crossover effects between civilian and military markets. Likewise, the U.S. UAV industry is waiting for government policy modification that will open the industry to the commercial market like never before, exponentially increasing sales of end items in the U.S. and worldwide.

Improvements to communications, fuel cells, and navigation have placed the unmanned systems industry at a critical point. Commercial interest in unmanned systems is beginning to increase dramatically as technology proven on the battlefield is adapted to civilian applications. While the U.S. has maintained unmanned system R&D expenditures for over 30 years, the recent spike in procurement due to wars in Iraq and Afghanistan has advanced the state-of-the-art more than ever, as companies attempt to out-innovate competing firms, searching for that *program of record* status. *Program of record* is not a standard term but is widely used to denote a program that has a valid capability document in JCIDS, is budgeted in the Future Years Defense Program, and has

gone through a Material Development Decision. The promise of commercial demand will continue this trend, although the combination of FAA regulations and U.S. government export controls dampen market enthusiasm.

3. *Point C: Major innovative breakthroughs predominantly come from lower-tier contractors and smaller companies*

Utterback's (1996) research emphasized the role of non-prime contractors in the development of innovative breakthroughs. Research proves this aphorism in all three historical industries.

Birkler et al. (2003) found this to be true in the fixed-wing aviation industry, with examples listed in the literature review. The first powered aircraft was invented by bicycle manufacturers. The eras with the highest numbers of entrants to the market witnessed the most intense competition and innovation. Many of those new companies brought with them breakthrough innovations that changed the industry.

Likewise, the microelectronics industry also saw major innovations come from upstarts, especially in the early Silicon Valley years. Companies like Texas Instruments, Fairchild, and Transistron established their presence in the marketplace with breakthrough innovations. Whereas fixed-wing innovations seem to occur most frequently in certain eras, the microelectronics industry sees almost constant innovation as processing and storage capabilities continually increase.

Like the two historical industries, unmanned systems breakthrough innovations have also originated largely from smaller companies. The most popular UAV design today, the Predator, was created in the garage of Abe Kareem ("The Dronefather," 2012). Likewise, AeroVironment revolutionized the man-portable UAV segment with their Pointer UAV, which proved its value in Afghanistan. Earlier UAVs were usually manned aircraft modified to be piloted remotely, carrying the traditional aircraft design features. The visionaries able to see beyond those designs came from the industry fringe, not from industry leaders.

As has been shown in this research, a company tends to be less inventive and take fewer risks the larger it becomes. As companies grow larger and go public, their

responsibility to shareholders leads them to more conservative and incremental development. Therefore, industry consolidation can have a detrimental effect on state-of-the-art evolution.

4. *Point D: Lapses in government attention to areas in both industries resulted in a loss of U.S. global dominance in those areas*

In both historical industries, the U.S. was at one time the global leader but saw that dominance slip. While the U.S. is still regarded as dominant in the fixed-wing aviation industry, it is no longer considered dominant in the microelectronics industry, where the majority of development and production has moved to Asia.

In the fixed-wing aviation industry, the research shows where government missteps resulted in industry decline. Although powered flight was invented in the U.S., the lack of government focus on the industry resulted in other nations overtaking the U.S. in aviation technology following WWI. The U.S. had to play catch-up in the years prior to WWII, which was aided by the recognition of overseas demand and the rise of commercial applications in the 1930s that kept companies competitive.

In contrast, it is difficult to place blame on the government for the decline of U.S. dominance in the microelectronics industry. The increased offshoring of semiconductor production combined with the growth of talent pools in Asia gradually eroded U.S. technological dominance in microelectronics. However, the VHSIC development history emphasizes the limitations of government. The government assumed that a dedicated development and procurement effort could leapfrog existing and forecast technologies but ended up fielding a technologically obsolete chip after years of research. The DoD underestimated the commercial electronics industry's ability to advance the state of the art and ended up in a costly but largely ineffective procurement process.

There is a contrast between the two historical industries that must be identified. The microelectronics industry primarily produces components, while this research primarily concerns architectural innovations in the fixed-wing industry. The leaching of microelectronics production overseas is primarily due to lower cost structures outside the U.S. Due to the global proliferation of microelectronics technologies, it is difficult to gain

a competitive edge in any one area, thus the lack of emphasis for production on U.S. soil. The fixed-wing aviation industry, however, benefits from the emphasis on nationalistic political influences and competitive advantage that ensure that production remains on U.S. soil.

The unmanned industry benefits from both situations. Commercial innovations in areas like propulsion systems and human–robot interface can be easily assimilated into defense architectures, while the DoD focuses on more sensitive technologies like sensor and weapon payloads to maintain competitive advantage over adversaries. Component technology innovations born globally can be easily assimilated into unmanned systems architectures, while more sensitive technologies born from U.S. R&D can help maintain global dominance.

The microelectronics industry history must be heeded in the current unmanned systems industry. The U.S. has been the unquestioned leader in unmanned systems development and procurement, but the global community is catching up. The rise and fall of U.S. technological dominance in the information technology industry can serve as a warning to the unmanned systems industry, which is currently threatened by unmanned systems proliferation throughout the globe. As stated in the literature review, the information technology industry, more so than the aviation industry, is very reliant on the pull of market demand. Countries such as Japan and Brazil have fewer government restrictions on the employment of unmanned systems and have seen their unmanned systems industry begin to grow rapidly. China has also recently invested heavily to develop its robotics industry (Tobe, 2013) and intends to be a key player in the industry future.

A statement by Pattillo (2000) on the status of fixed-wing aviation in 1923 has interesting echoes today: “By 1923 there were rising concerns about the lack of aviation policy, even as the role of aviation grew, especially in such fields as agriculture, forestry photography, and mapping (p. 57).”

One can easily apply this quote directly to the current unmanned systems industry. Today, there are concerns about the lack of a well-defined unmanned systems policy. FAA flight restrictions, export controls, and legal issues associated with

unmanned vehicles sharing public spaces with humans all serve to dampen the prospects of industry growth and development. I believe that the next few years will be the most critical in determining the future of the U.S. unmanned systems industry, if the government can avoid the same lapses in attention that significantly affected the two historical industries.

5. *Point E: Flexibility in the procurement process can increase lead user input and result in more rapid fielding of innovative breakthroughs*

The fixed-wing aviation and microelectronics industries must be approached from different angles when discussing procurement processes. Whereas fixed-wing aviation procurement predominantly involves substantial programs of record where the end item is an assembled aircraft, microelectronics procurement consists of buying component technologies to be installed in other architectures. Therefore, it is easier to demonstrate flexibility in the microelectronics industry than the fixed-wing aviation industry.

However, the history of fixed-wing aviation is filled with examples of flexibility in the procurement process. The early years are characterized by many variant airframes but low production volumes of any one airframe. This permitted the testing of most variants in an operational environment, where each variant's pros and cons could be most effectively analyzed. The choice between variants became much clearer in the operational environment. The unmanned systems industry today is very similar. Particular warfighter needs have been addressed with a multitude of unmanned system variants, allowing for testing and evaluation in actual combat environments with minimal risk to humans. As the research shows, market demands are already being felt, with the cancellation of truck-mounted UAV systems in favor of man-portable or runway-launched systems.

I presented a specific example from the microelectronics industry of how a firm persuaded a contracting officer to switch technologies of a Minuteman II transistor mid-production. The relative ease of changing component technology led to this recurring often during industry evolution. Indeed, the procurement process for microelectronics had to be flexible, since specific examples show that semiconductors developed and procured by the DoD were often inferior to commercial products by the time they were fielded.

Likewise, in the unmanned systems industry the research shows close collaboration between the warfighter and the contractor, such as with the performance based logistics process. This collaboration allows for quicker industry response to requirement modification, where architectural and component changes can be made outside the normal, lengthy acquisition channels.

The unmanned systems industry is rife with examples of unconventional procurement processes. The past decade has resulted in a dramatic shortening of the lead user feedback loop, favoring rapid employment over drawn-out procurement processes that sacrifice flexibility for efficiency. As combat operations in Afghanistan wind down, the threat is that procurement practices will gradually return to the pre-war state, with a focus on exploitation of existing technologies instead of exploration for new breakthroughs in an attempt to save money. The lead user feedback loop will inevitably be lengthened, as program justification will have to come from higher up the chain of command.

6. *Comparative analysis summary*

While there are obvious differences and important contrasts between the three industries, the framework suggested above contains enough similarities to adequately compare the early eras of fixed-wing aviation and microelectronics and the unmanned systems industry. These historical industries can advise policy decisions in the unmanned systems industry and serve as a warning to government inattention to what has been identified as a critical part of the U.S. defense strategy for the foreseeable future.

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VI. THE UNMANNED SYSTEMS INTEGRATED ROADMAP VERSUS THE BUDGET

The first part of this chapter shows overall and individual program unmanned systems budget projections through FY2018. The second part of this chapter details technology readiness levels for many key technologies mentioned in the Unmanned Systems Integrated Roadmap, which may be referred to as the *Roadmap* for the remainder of the thesis. I attempt to determine if the DoD's budget policy is in line with its desire to advance unmanned systems technologies.

The DoD produces the Roadmap every two years. The Roadmap “describes the vision for the joint integration of unmanned systems into the Department and identifies steps required to affordably facilitate this integration” (*FY2013–2038 Unmanned Systems*, 2013, p. xiii) and “outlines major areas over the next 25 years where DoD and industry should focus to ensure the timely and successful adoption of unmanned systems technologies” (*FY2013–2038 Unmanned Systems*, 2013, p. xiii).

A. FUNDING THROUGH 2018

1. Overall Funding Detail

Figure 16 shows a relatively stable flow of UAV funding. Although procurement increases from \$1.5 billion in 2014 to \$2.2 billion in 2018, RDT&E declines from \$1.2 billion in 2014 to \$1.1 billion in 2018. This trend seems to portend an increase in exploitation of existing technology vice further exploration. The Roadmap (2013) cited the forecasted worldwide robotics industry growth but stated that although “DoD will not be the bulk user within that market” (p. 4), it “does intend to be the most innovative user” (p. 4). While the DoD counts on market growth, it seems as though U.S. government policies like FAA restrictions and expert regulations will hamper U.S. robotics industry growth, while international firms unburdened by U.S. regulations will have better growth opportunities.

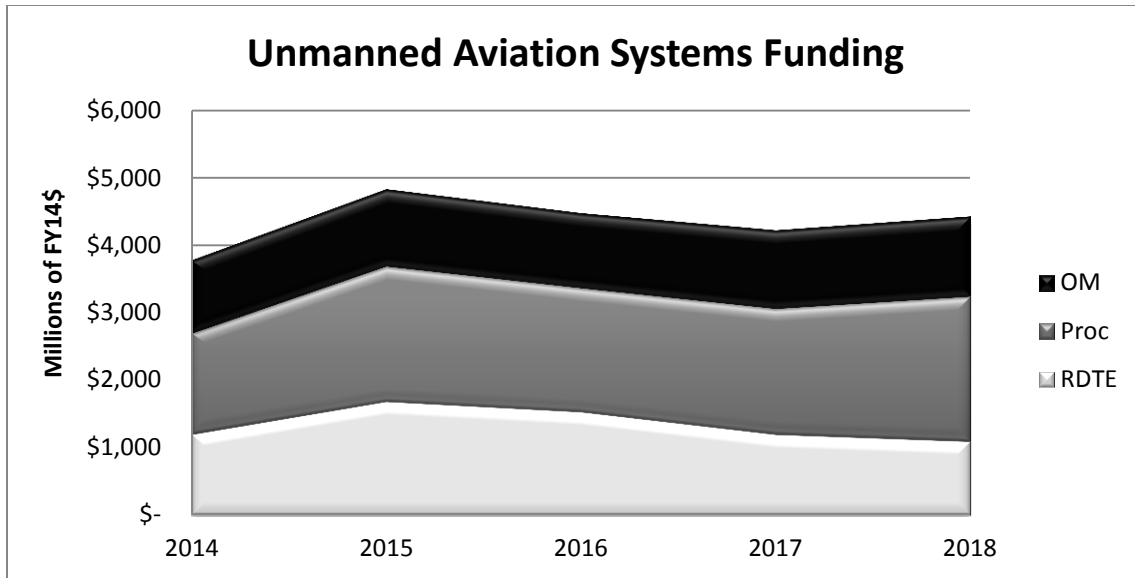


Figure 16. Unmanned Aviation Systems Funding through FY2018 (after *FY2013–2038 Unmanned Systems*, 2013)

Figure 17 shows unmanned ground systems funding through 2018. RDT&E reaches a peak in 2015 at \$19.1 million but drops sharply to \$10.6 million by 2018. Note that expenditures on unmanned ground systems are a small fraction of that spent on unmanned aviation systems. The Roadmap (2013) stated that this unmanned ground systems support and sustainment plan sustains “specific capabilities beyond today’s worldwide engagements to bridge the capability gap until enduring capabilities are developed and acquired using traditional Armed Services programming” (p. 7).

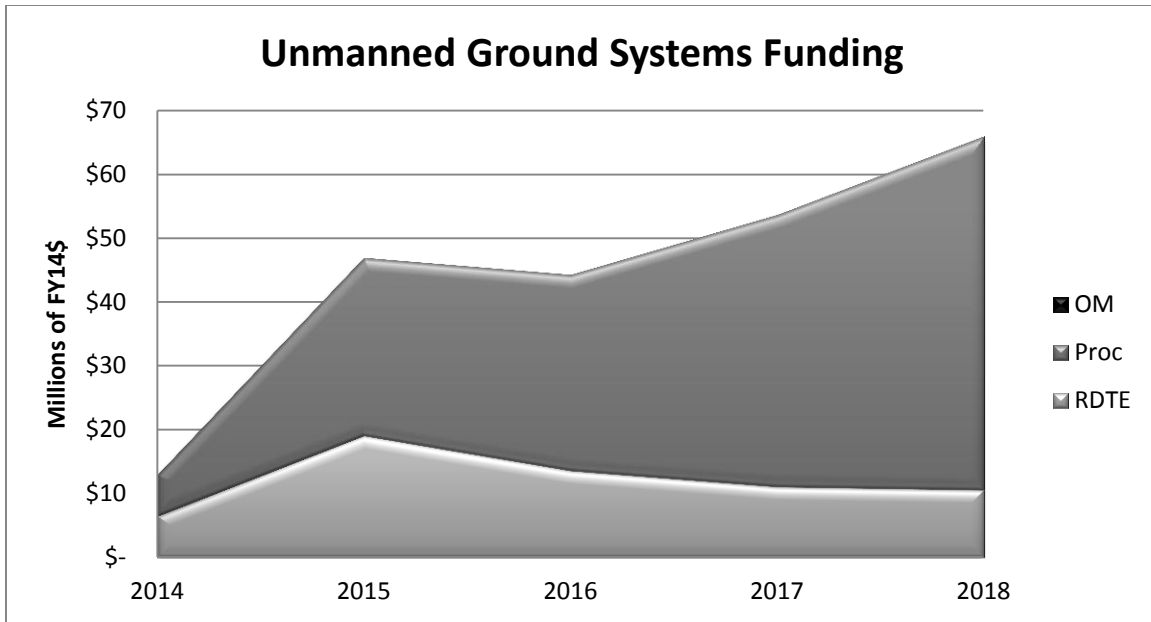


Figure 17. Unmanned Ground Systems Funding through FY2018 (after *FY2013–2038 Unmanned Systems*, 2013)

Figure 18 shows maritime systems funding through 2018. RDT&E increases from \$62.8 million in 2014 to \$87.2 million in 2018. While procurement increases from 2015 to 2017, FY2018 procurement funding is less than that in 2014. The Roadmap (2013) predicted that “as new littoral combat ships arrive in service, support unmanned maritime systems (UMS) will rise in number” (p. 8).

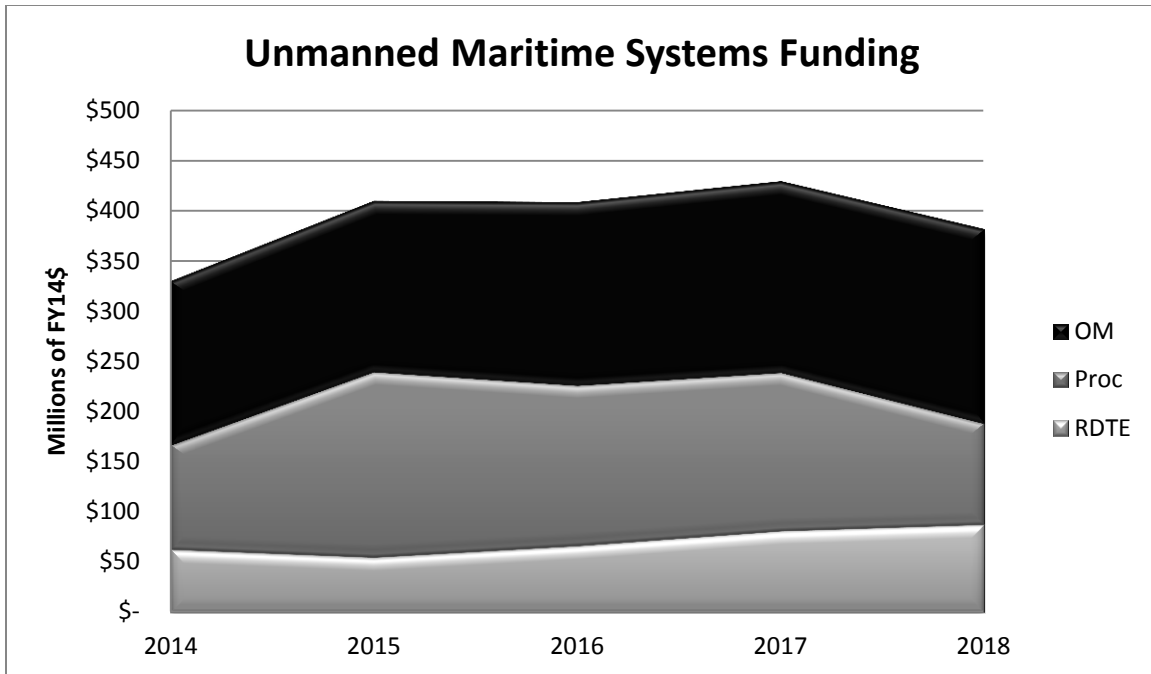


Figure 18. Unmanned Maritime Systems Funding through FY2018 (after *FY2013–2038 Unmanned Systems*, 2013)

Figure 19 shows DoD unmanned systems funding as a percentage of total DoD funding FY2014 through 2018. Although labeled as a priority for the DoD, total unmanned systems funding is not projected to make up more than 1% of the total DoD budget through 2018.

Funding is in millions of TY\$/PB14			
FY	DoD Unmanned Systems Funding	Total DoD Funding	Percentage
2014	\$4,119.10	\$526,622.00	0.782%
2015	\$5,276.20	\$540,839.00	0.976%
2016	\$4,920.50	\$551,369.00	0.892%
2017	\$4,700.40	\$559,967.00	0.839%
2018	\$4,867.10	\$568,571.00	0.856%

Figure 19. DoD Unmanned Systems Funding as a Percentage of Total DoD Funding (after *FY2013–2038 Unmanned Systems*, 2013)

To put the unmanned systems budget in perspective, Figure 20 shows Air Force and Navy funding for the F-35 Joint Strike Fighter through FY2018. Except for 2015, funding for the JSF is more than twice that for all unmanned systems funding, and FY2018 JSF funding is almost three times that of unmanned systems.

Funding is in millions of TY\$/PB14			
FY	DoD JSF Funding	Total DoD Funding	Percentage
2014	\$8,257.38	\$526,622.00	1.568%
2015	\$9,519.03	\$540,839.00	1.760%
2016	\$11,277.54	\$551,369.00	2.045%
2017	\$12,143.02	\$559,967.00	2.169%
2018	\$13,496.24	\$568,571.00	2.374%

Figure 20. JSF Funding as a Percentage of Total DoD Funding (after IHS Aerospace, Defense, & Maritime, 2013)

Although funding for unmanned systems seems relatively healthy and stable, it still represents a small fraction of total DoD funding. Total unmanned systems spending seems smaller still when compared to funding for large DoD programs of record.

2. Individual Program Funding Detail

The previous three figures provided information about funding for the unmanned systems industry as a whole but did not provide much detail as to how the money was spent. Therefore, I am including data from IHS Aerospace, Defense, & Maritime Jane's budget analysis for FY2014, which displays each service's activity priority list and budget forecast through 2018. Budget information from 2011 is included in each chart to show recent trends. The monetary value for each service program includes that program's RDT&E and procurement budget. The values in the y-axis are in millions of then-year dollars. Individual system budget data are available for programs of record. Systems that are not yet programs of record, such as the K-Max unmanned cargo helicopter, are consolidated into other funding categories, such as science & technology (S&T).

The Individual Program Funding Detail does not include off-platform operations and maintenance (O&M) costs; therefore, it is only a partial picture of total funding requirements for unmanned systems. Data are not yet available to show the full operations and maintenance costs to the DoD for each program. Immaturity in technologies such as autonomy and communications keep these O&M costs higher than desired. Only with technology maturation will these O&M costs decrease.

Figure 21 shows budget forecasts for the RQ-4 Global Hawk/Triton Program. The RQ-4 is the most expensive unmanned system per copy in the DoD inventory. While funds increase for the Naval variant, funds for the Air Force variant drop sharply, with an overall decrease in funding for both programs between 2011 and 2018. Naval variant funding fluctuates erratically through 2018.

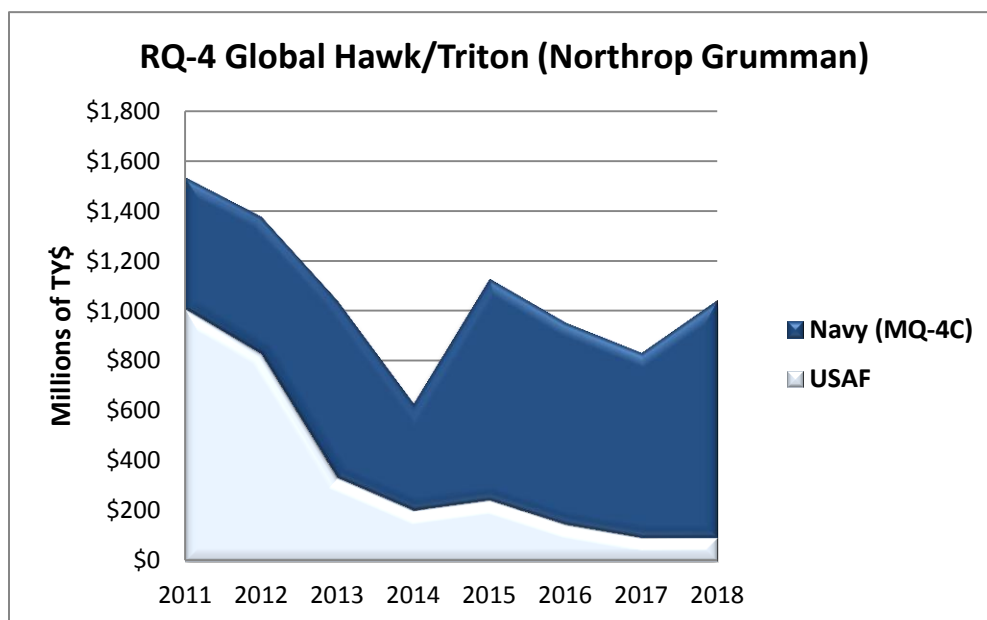


Figure 21. FY2011—2018 Budget for RQ-4 UAV (after IHS Aerospace, Defense, & Maritime, 2013)

Figure 22 shows forecasted funding for the General Atomics MQ-1/MQ-9 variants. While decreasing from highs in 2012, funding roughly stabilizes through 2018.

Air Force funding remains stable through 2018, but Army variant funding almost zeroes out after 2016. Also important to note is that the MQ-9 is a larger and more costly airframe than the MQ-1.

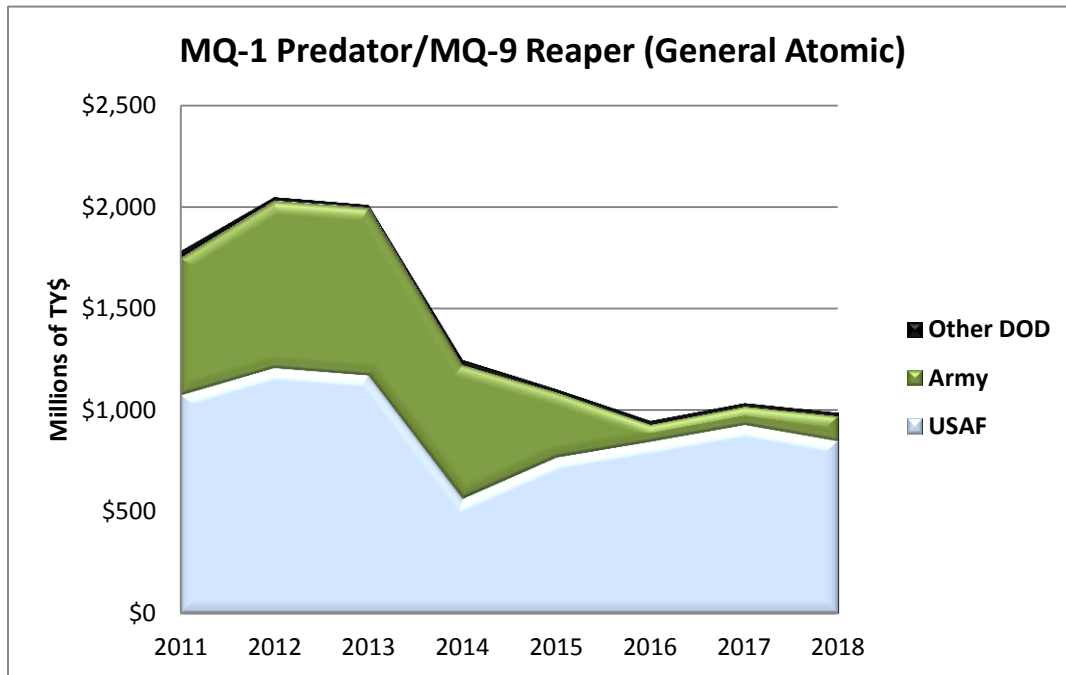


Figure 22. FY2011—2018 Budget for MQ-1/MQ-9 UAV (after IHS Aerospace, Defense, & Maritime, 2013)

Figure 23 and Figure 24 show funding for the Navy UCAV and UCLASS. The UCAV is a technology demonstrator; therefore funding will taper off by 2015. The UCLASS will see increases in funding to 2016, and funding will stabilize into the foreseeable future.

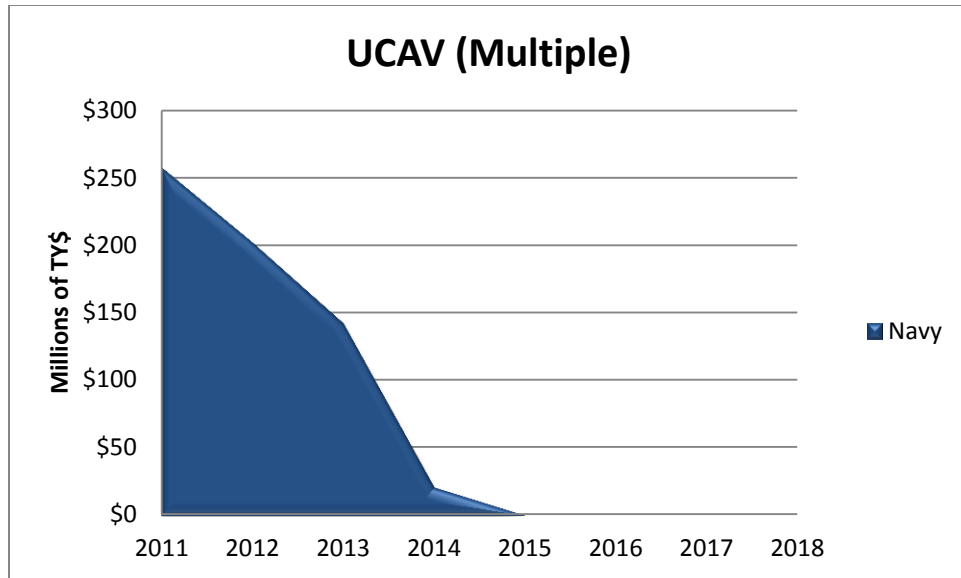


Figure 23. FY2011–2018 Budget for UCAV UAV (after IHS Aerospace, Defense, & Maritime, 2013)

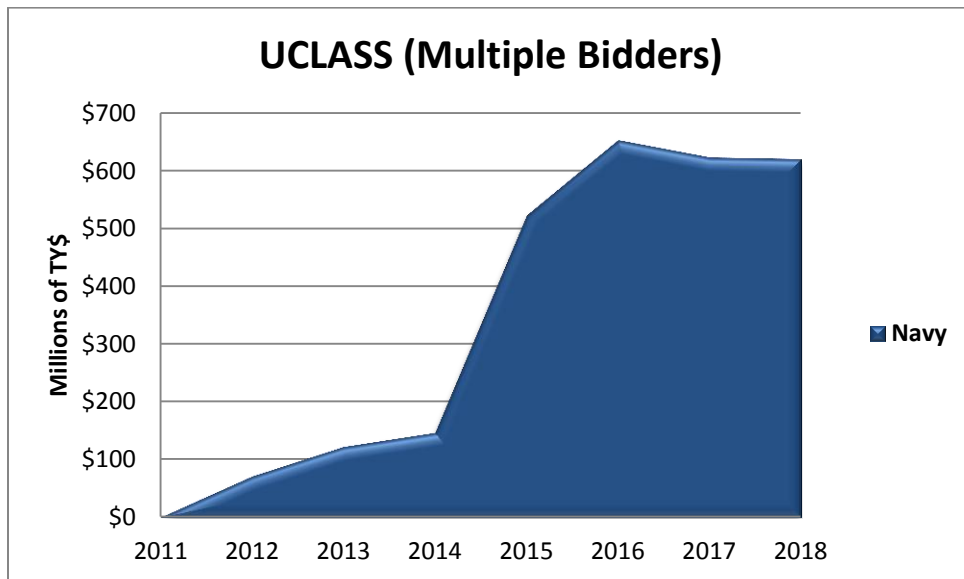


Figure 24. FY2011–2018 Budget for UCLASS UAV (after IHS Aerospace, Defense, & Maritime, 2013)

Funding for the RQ-7 Shadow is shown in Figure 25. Funding declined rapidly from 2011 but stabilizes from 2012 on, as the Shadow is a program of record and will continue to be procured by the Army through 2018.

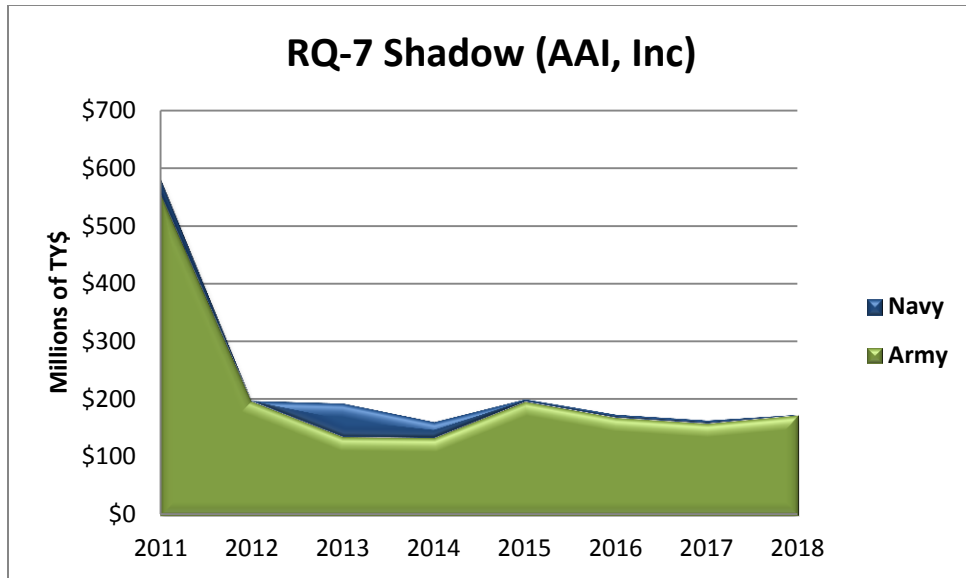


Figure 25. FY2011–2018 Budget for RQ-7 UAV (after IHS Aerospace, Defense, & Maritime, 2013)

Funding for the MQ-8B Fire Scout will increase in 2016 but will sharply decline thereafter, as shown in Figure 26. The MQ-8 is an unmanned rotorcraft vehicle capable of offensive fires.

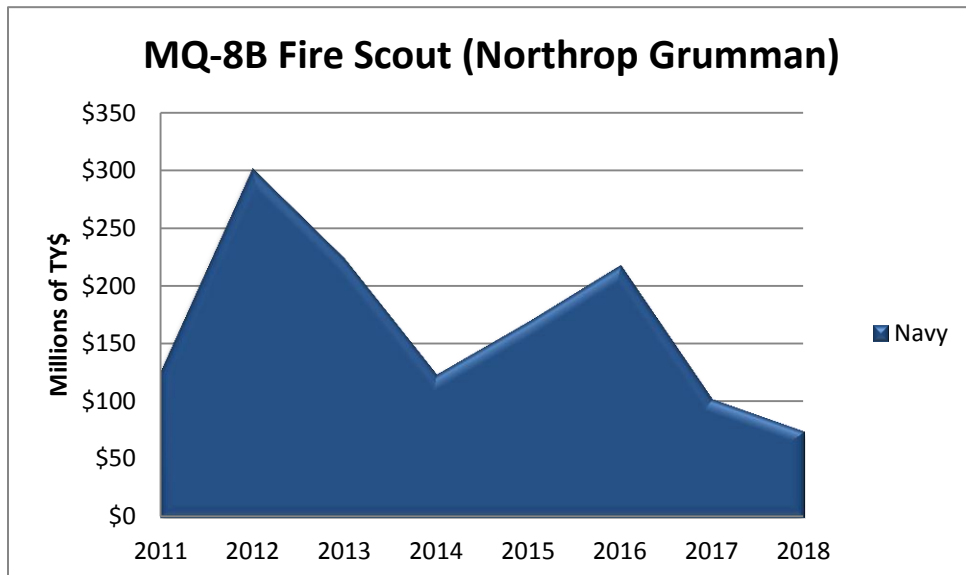


Figure 26. FY2011–2018 Budget for MQ-8 UAV (after IHS Aerospace, Defense, & Maritime, 2013)

From a high of more than \$90 million in 2012, funding for the RQ-11 Raven declines to less than one-fourth of the 2012 value by 2018, as seen in Figure 27.

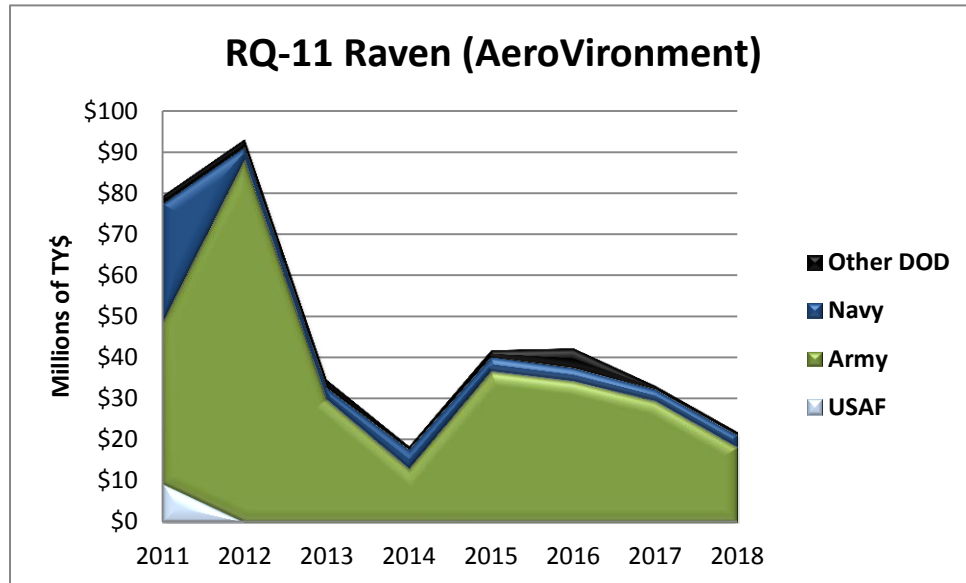


Figure 27. FY2011–2018 Budget for RQ-11 UAV (after IHS Aerospace, Defense, & Maritime, 2013)

Funding for the MQ-5 Hunter slowly declines to almost one-third of the 2011 value, as shown in Figure 28.

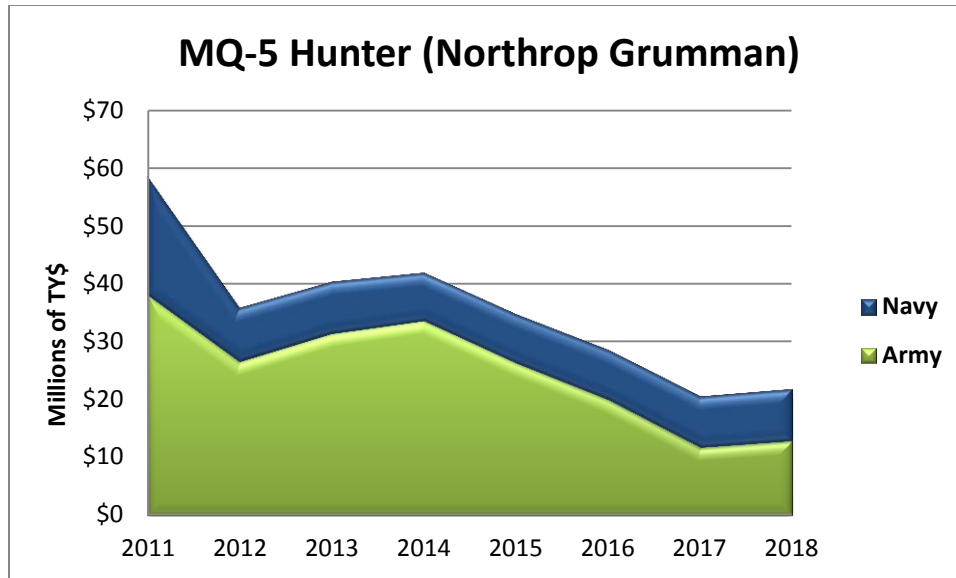


Figure 28. FY2011–2018 Budget for MQ-5 UAV (after IHS Aerospace, Defense, & Maritime, 2013)

Funding for the AeroVironment Endurance UAV variants declines sharply from \$165.9 million in 2011 to zero in 2016, but the Army funding value for 2018 is a nominal \$100 million, as seen in Figure 29.

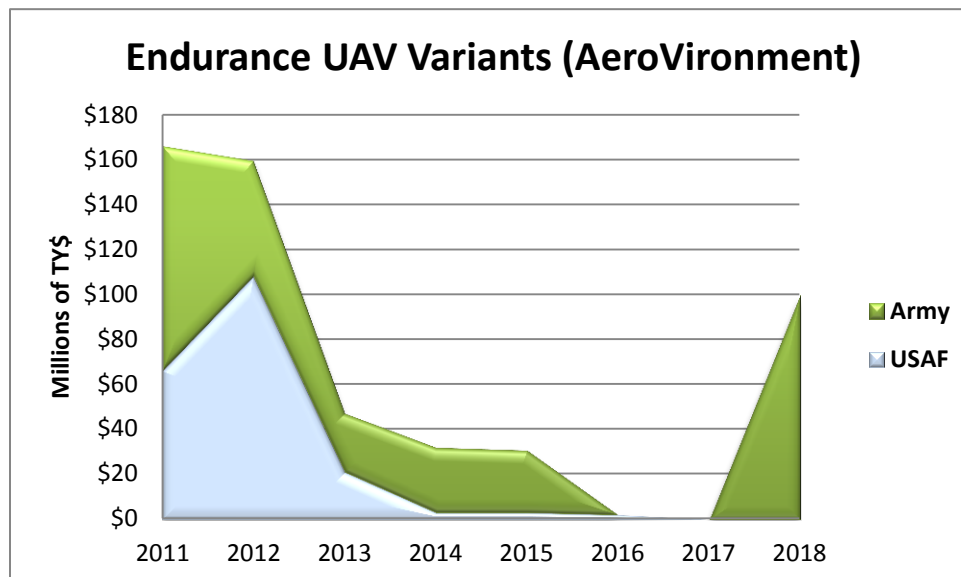


Figure 29. FY2011–2018 Budget for Endurance UAV (after IHS Aerospace, Defense, & Maritime, 2013)

Funding for the RQ-21 STUAS/STUASLO gradually increases and stabilizes through 2018 as it enters low-rate production, as seen in Figure 30.

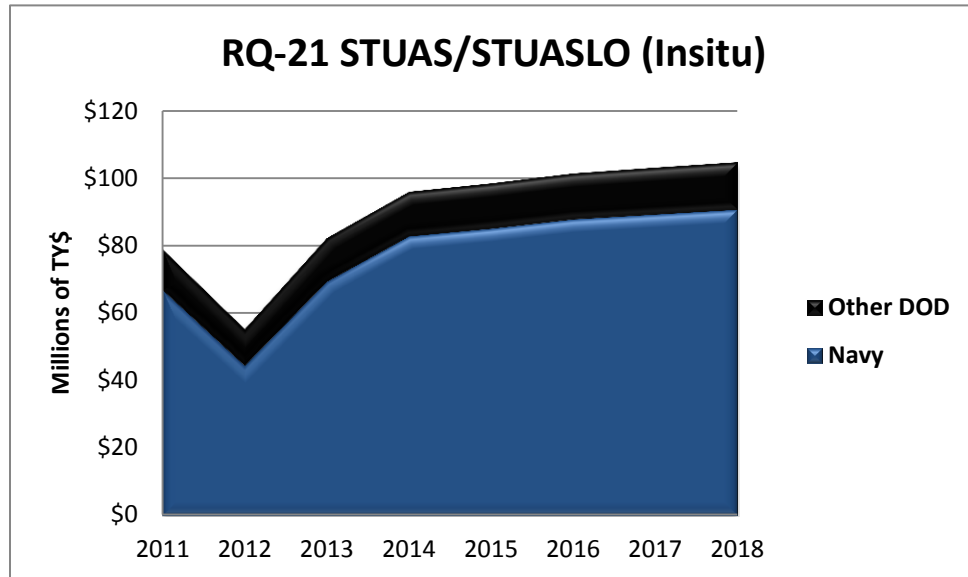


Figure 30. FY2011–2018 Budget for RQ-21 UAV (after IHS Aerospace, Defense, & Maritime, 2013)

Funding for target drone development and procurement remains relatively stable through 2018, as seen in Figure 31.

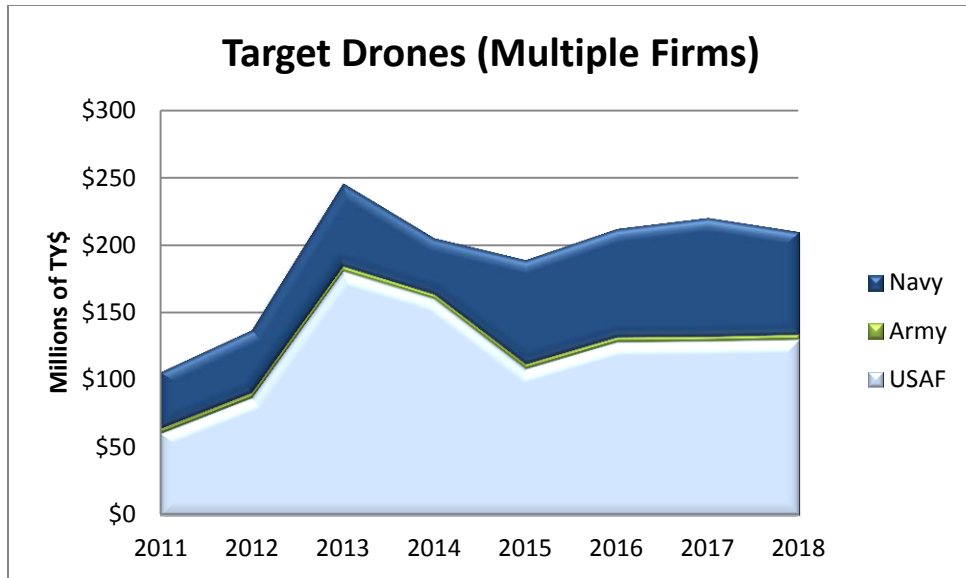


Figure 31. FY2011–2018 Budget for Target UAVs (after IHS Aerospace, Defense, & Maritime, 2013)

DoD funding for the common development of UAS systems sharply declines to about one-tenth the 2011 value, as seen in Figure 32.

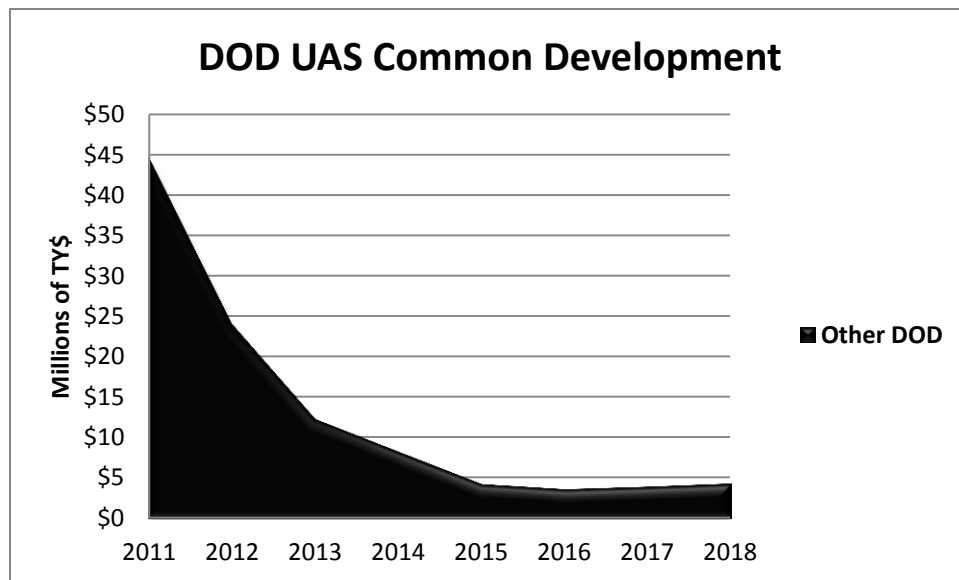


Figure 32. FY2011–2018 Budget for DoD Common UAS Development UAV (after IHS Aerospace, Defense, & Maritime, 2013)

The Army and Navy both list a General UAS Funding category in their budgets, with Navy funding cut off past 2012 and Army funding ending in 2014, as seen in Figure 33.

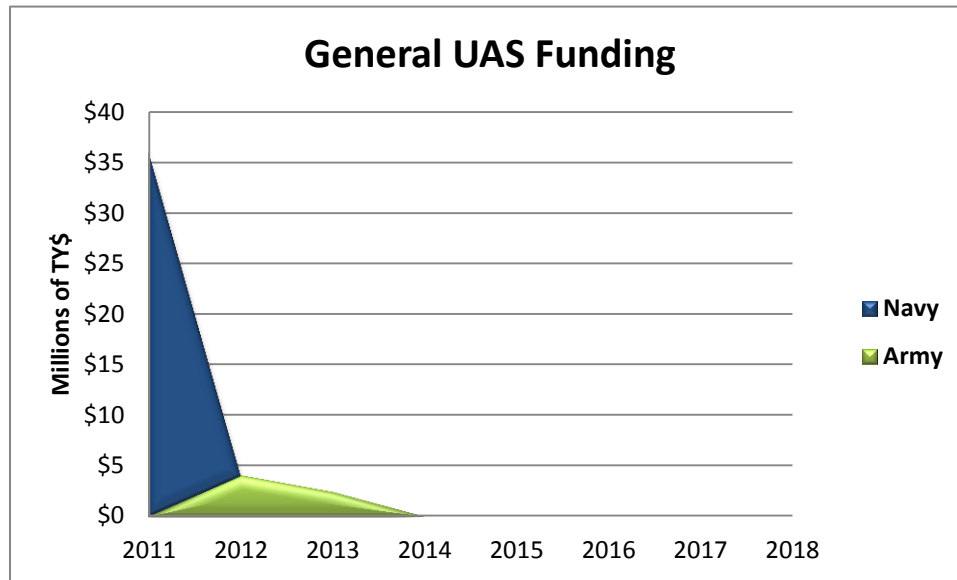


Figure 33. FY2011–2018 Budget for General UAV Funding (after IHS Aerospace, Defense, & Maritime, 2013)

DoD funding for the Joint Robotics Program ends in 2013 and zeroes out through 2018, as shown in Figure 34.

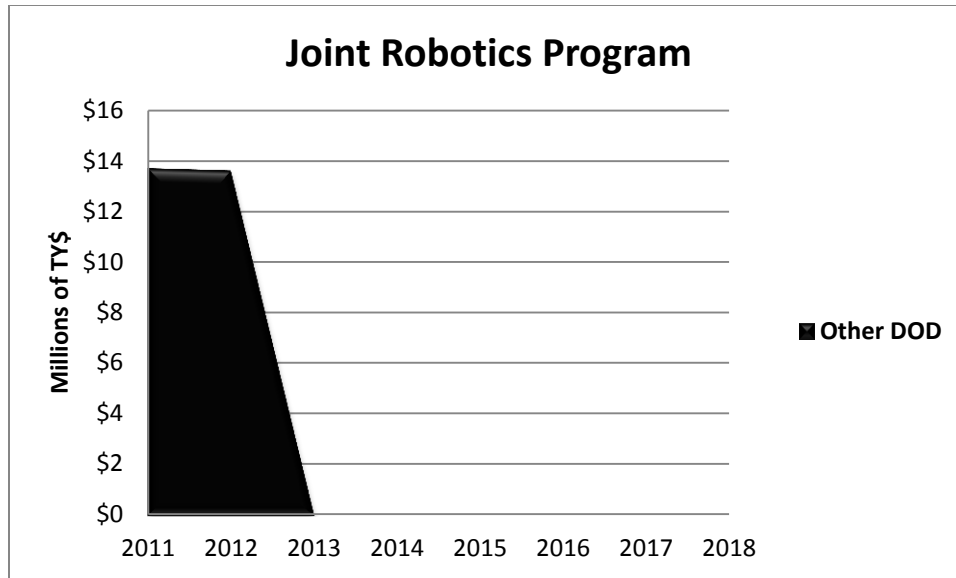


Figure 34. FY2011–2018 Budget for Joint Robotics Program (after IHS Aerospace, Defense, & Maritime, 2013)

Navy EOD robotics funding, as seen in Figure 35, is one of the few programs that sees an increase in funding, although the dollar value remains relatively small.

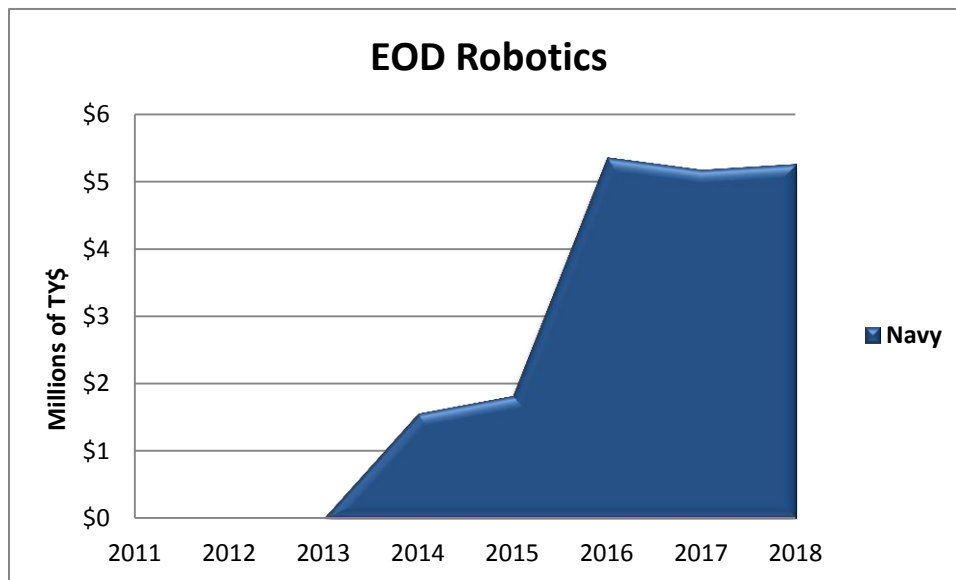


Figure 35. FY2011–2018 Budget for Navy EOD Robotics (after IHS Aerospace, Defense, & Maritime, 2013)

Figure 36 shows funding for anti-submarine warfare targets, which are unmanned underwater vehicles used to simulate enemy submarines. Funding is erratic through 2018.

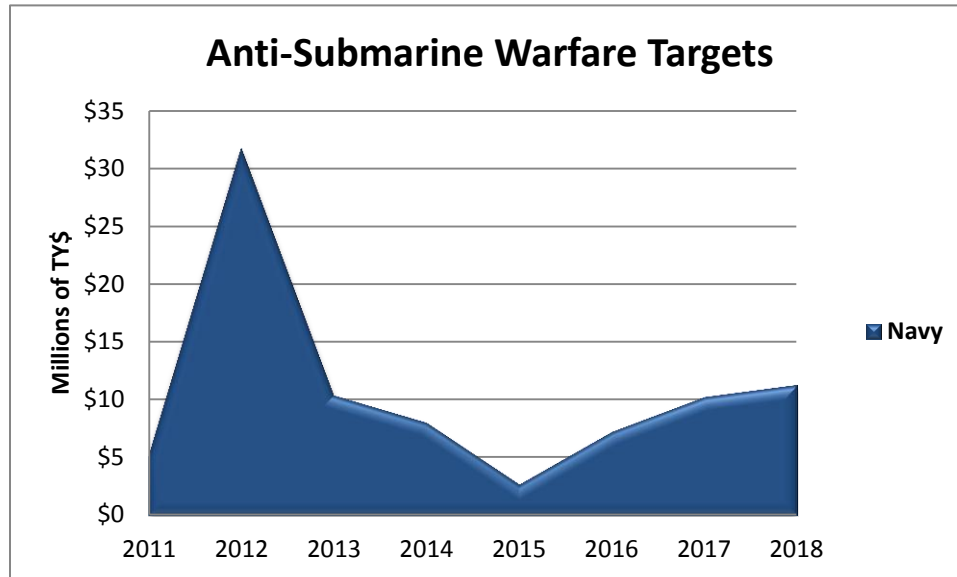


Figure 36. FY2011–2018 Budget for Anti-Submarine Warfare Targets (after IHS Aerospace, Defense, & Maritime, 2013)

The following two graphs, Figure 37 and Figure 38, show funding for sensor technologies incorporated on unmanned systems. Both show spikes in funding followed by sharp declines.

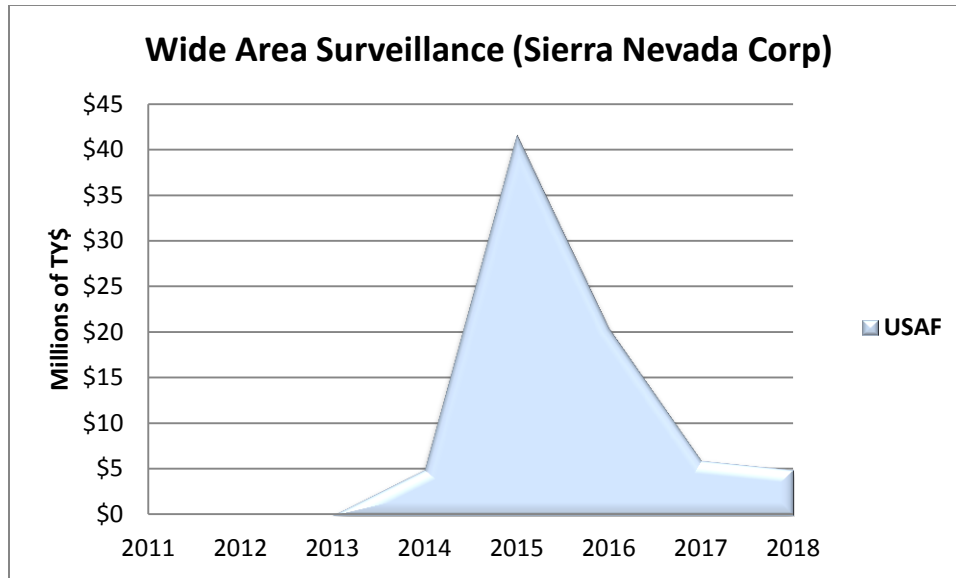


Figure 37. FY2011–2018 Budget for Wide Area Surveillance (after IHS Aerospace, Defense, & Maritime, 2013)

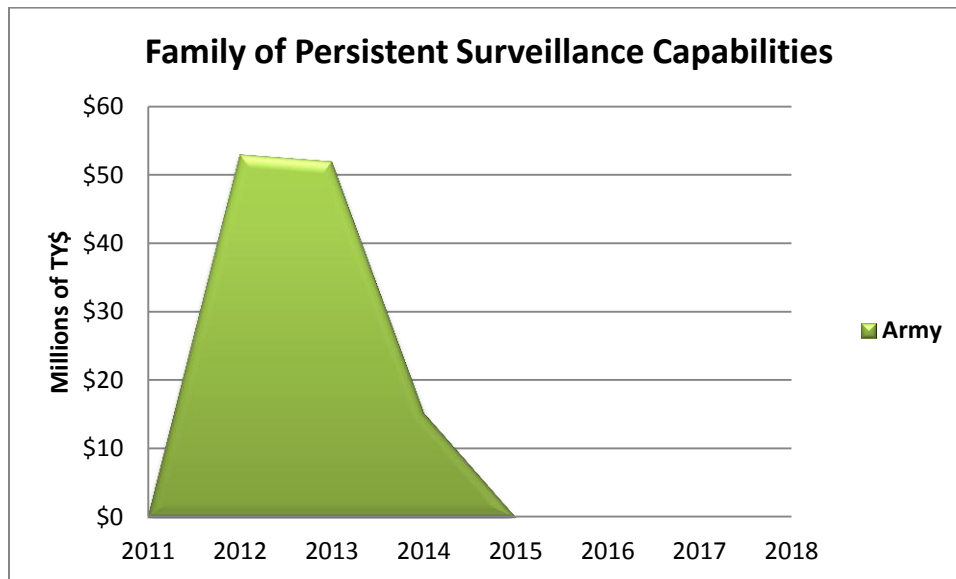


Figure 38. FY2011–2018 Budget for Family of Persistent Surveillance Capabilities (after IHS Aerospace, Defense, & Maritime, 2013)

Although declining sharply in 2014, funding for the Rapid Technology Transition Program increases through 2016 and then stabilizes, as shown in Figure 39. Again, these data are not exclusive to unmanned systems technologies.

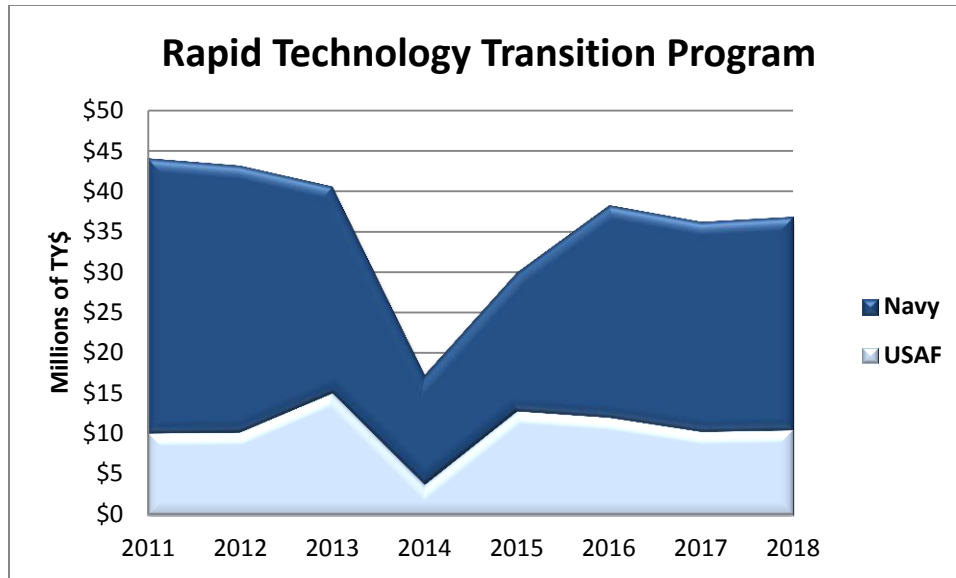


Figure 39. FY2011–2018 Budget for Rapid Technology Transition Program (after IHS Aerospace, Defense, & Maritime, 2013)

Figure 40 shows the rise in JUON funding through 2014, followed by a stable flow through 2018. Although the dollar value is relatively small, these data indicate the acknowledged importance of the JUON process, which shortens the lead user feedback loop and gets desired technologies to the field faster.

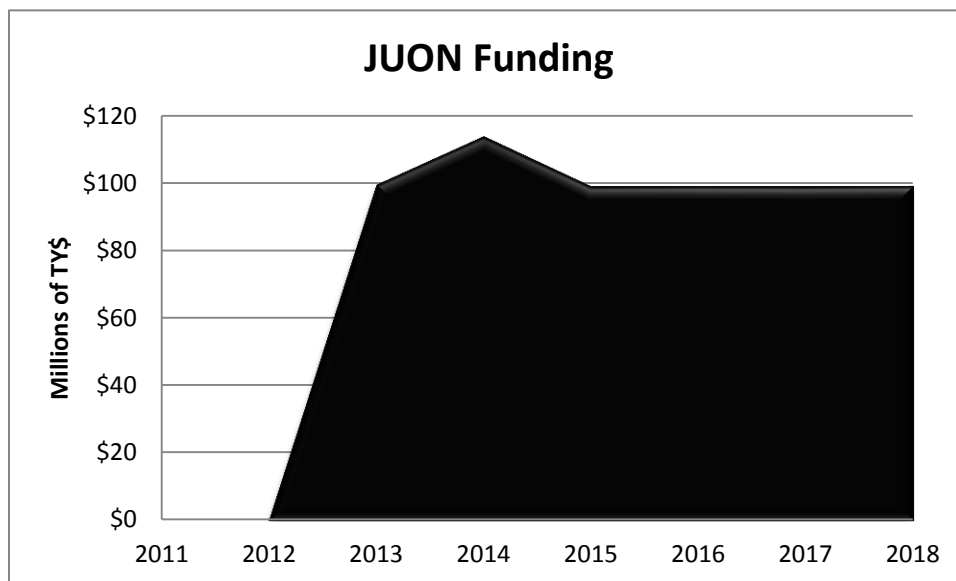


Figure 40. FY2011–2018 Budget for JUON Funding (after IHS Aerospace, Defense, & Maritime, 2013)

Overall, individual activity budget data are consistent with the Roadmap (2013) funding information, but this research draws an important conclusion from the data. Funding for the major programs, like the MQ-4, MQ-1, MQ-9, and UCLASS, remains substantial but is in decline. Funding for the largest programs is going to established contractors Northrop Grumman (MQ-4) and General Atomics (MQ-1 and MQ-9), while the UCLASS is currently being bid by Boeing, Northrop Grumman, Lockheed Martin, and General Atomics. Smaller programs and smaller companies, like the RQ-7 (AAI, Inc.) and RQ-11 (AeroVironment), and companies that develop the less touted ground and maritime systems generally see greater declines in funding and less stable cash flows, with a few exceptions. This trend is indicative of the DoD's desire to narrow down on technologies to achieve efficiencies.

These data seem to indicate that the DoD has chosen dominant designs that will see further development and procurement at the expense of other systems. The Global Hawk and Predator-type designs are receiving the majority of funding, while the UCLASS program will eventually determine the dominant carrier-based design. It is difficult to determine where on the technology S-curve these architectures fall, but given the immaturity of the industry the DoD could be at risk of putting most of its eggs in too few baskets.

B. TECHNOLOGY READINESS LEVEL OVERVIEW

In order to show the immaturity of key unmanned systems technologies, I consulted the independent research and development (IR&D) database provided by the Defense Technical Information Center (DTIC). I received a data set filtered for all entries associated with the term "unmanned." It is important to note that some of the technologies are proprietary and cannot be fully divulged, so I have tried to be as generic as possible describing the technology area. Also, the TRL value is where the technology is expected to be at the end of the current development phase, which means that most of the technologies are not yet at that level. One major limitation of the database is that there is no estimation of how much time it will take to get the technology to that level or

beyond. Another limitation is the chance that not all critical technologies are depicted in the database due to sensitivity concerns. For more information on TRL ratings and descriptions, refer to Appendix A.

The Roadmap (2013) divided unmanned systems technologies into nine major categories and expounds on five of those. I too have broken out those five categories and included pertinent information. I combined all other TRLs into the final table.

1. Interoperability and Modularity

The Roadmap (2013) defined interoperability as “the ability to operate in synergy in the execution of assigned tasks” (p. 31) with the ability to “provide data, information, material, and services to and accept the same from other systems, units, or forces ... and to use the exchanged data, information, material, and services to enable them to operate effectively together” (p. 31). DoD policy states that systems employed by the DoD shall be interoperable with joint, combined, coalition, and other government agencies as appropriate (DoD, 2007). Rapid procurement methods used in the past decade for unmanned systems have not always adhered to this requirement, due to the urgency of need in battle. As combat operations in Afghanistan conclude, there will be a greater effort at ensuring interoperability at program onset. Figure 41 is the OSD interoperability roadmap.

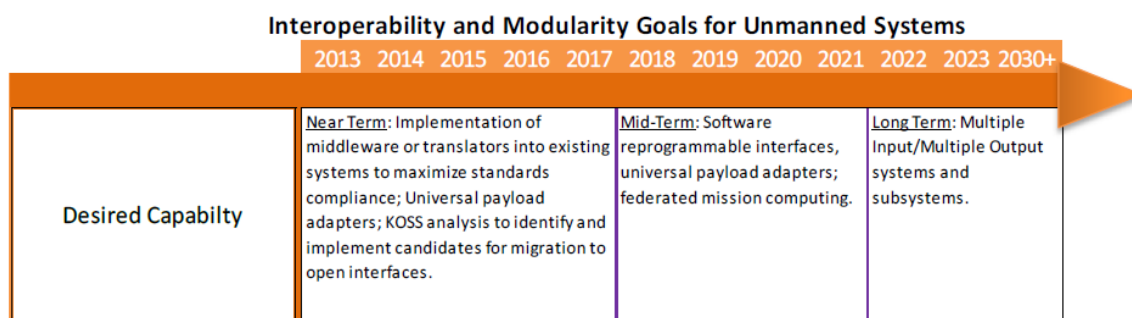


Figure 41. Interoperability and Modularity Roadmap (from *FY2013–2038 Unmanned Systems*, 2013)

Table 2 displays the following information about unmanned systems interoperability and modularity TRLs:

Table 2. Interoperability Technology Summary (after J. W. Smith, personal communication, September 9, 2013¹)

Look beyond existing technologies and manned/unmanned platform modernization plans to examine how future capabilities can provide increased performance, affordability, and relevance.	2
Developing a family of platform agnostic UAS products to enhance Command and Control and Mission Management market segments	2
Identify the key risk areas of the RMMV (Remote Multi-Mission Vehicle) operation with LCS (Littoral Combat Ship)	3
Integrate and demonstrate a Multi-Intelligence UAS mission solution to include sensors on both Sentry and Neptune Air Vehicles.	3
Integrated hardware/software architecture for supporting Unmanned Aerial System (UAS) missions with varying levels of autonomy	4

As Table 2 shows, unmanned systems interoperability technologies are immature and will need time and effort to advance them, as well as possibly retrofitting existing unmanned systems as the technology matures.

2. Communication Systems, Spectrum, and Resilience

The Roadmap (2013) combined “availability of communications link, the amount of data that the communications links support, obtaining spectrum assignments, and the

¹ Mr. J. W. Smith, Chief of the DTIC Information Collection Division, provided an unclassified data set for current program TRLs via email on September 9, 2013.

resilience of all RF subsystems against interference” (p. 39) into this category. The Roadmap (2013) identified several issues with the current infrastructure: poor global connectivity, costly satellite/network contracts, stovepipe infrastructures, and poor information sharing. Unmanned systems will be vigorously competing with commercial systems for broadband in the foreseeable future and must also be able to withstand electromagnetic attacks in more contested airspace than encountered in Iraq and Afghanistan. Figure 42 is the capability roadmap.

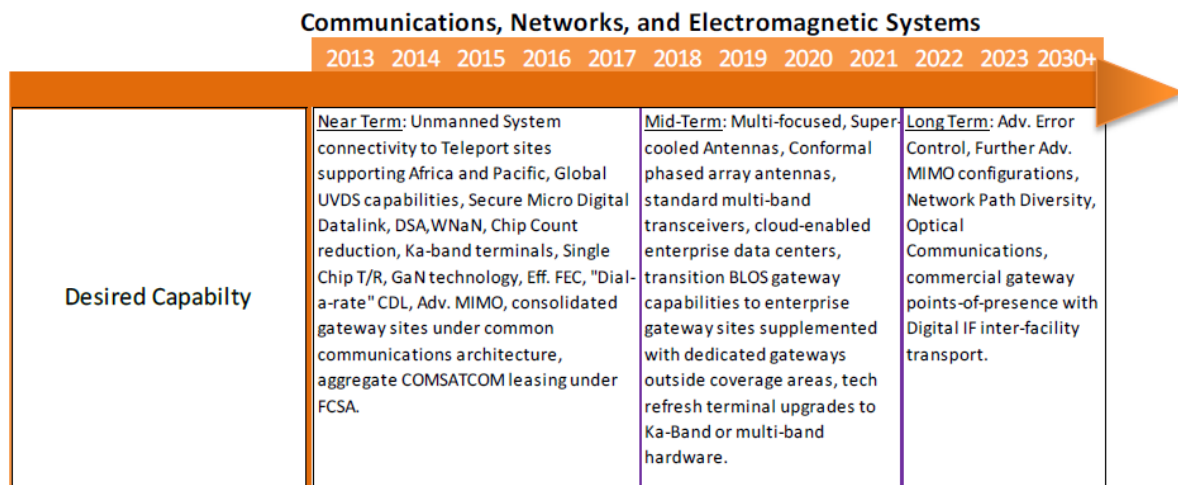


Figure 42. Communications, Networks, and Electromagnetic Systems Roadmap (from *FY2013–2038 Unmanned Systems*, 2013)

Table 3 shows the TRLs for communications systems from the IR&D database I received. This category had the highest concentration of immature technology. Many of the technologies deal with low observability and survivability in contested airspace, which will become more important as global counter-UAV technologies mature.

Table 3. Communications Systems Technology Summary (after J. W. Smith, personal communication, September 9, 2013)

New prototype and production radar systems testing (further information withheld)	1
Identify and develop the core technologies for enabling miniaturized Free Space Optical Communications systems capable of scaling across data rates, distances, and platforms and integrating with radio frequency systems for adjunct capabilities.	2
A solution that allows the UAS to maneuver to maintain safe separation from other threat aircraft, which relies on less restrictive separation distances than conflict avoidance	2
Develop a low cost, compact, and light weight electronically steerable antenna for Ka SATCOM in Unmanned Aircraft Systems (UAS).	2
Advance objective in the use of natural language processing algorithms to produce inductive reasoning in task-commanded robots	2
High data rate for SATCOM beyond line-of-sight (BLOS) manned and unmanned aircraft operating with small antennas and/or low profile low observable antennas	2
Enhanced Global Observer system reliability, airworthiness and flight safety	2
Analyze and develop Counter-UAS tracking and intercept algorithms, understanding system capabilities and limitations for specific use in C-UAS mission scenarios	2

Predicting and Optimizing Performance of a Maritime Data Link with a Low Freeboard Node	3
Ability for robots to build maps without emitting energy	3
Circular Array Antenna (electronically steered directional Ku-band circularly polarized antenna offering electronic steering with no moving parts in a design that is low cost, low profile, and compact)	3
Techniques to counteract jamming, spoofing, and detection	3
Expand the capabilities of the Wideband Relay System	3
Scalable Agile Beam Radar (SABR) Receiver Exciter Processor enhancements for shipboard UAV operations	3
Wideband analog pre-processor for spatial multiplexing	3
Techniques for controlling underwater autonomous devices from long stand-off range	3
On-Demand Medium Area Surveillance (O-DMAS) sensors for UAVs	4
Robust navigation capability for autonomous ship-based landing and recovery in GPS denied environment	4
Small form factor radio frequency countermeasures hardware, software and firmware	4
Algorithms and Pilot Displays to aid in adding to the UAV pilot's situational awareness	4
Modern smart phone technology able to control military	4

systems	
Highly automated data exploitation	5
Wide-area motion imagery exploitation capabilities	5
Signals intelligence geo-location capability that will fit on small UAS	5
Leveraging ground cellular infrastructure to provide low cost aircraft to ground broadband connectivity	5
Multi-channel, phase coherent, direction finding radio frequency sensors deployable on UAS capable of prosecuting multiple signal types.	5
Architecture artifacts that enable civil and military UAS integration in the national airspace system, concentrating primarily on data sharing	6
Remotely piloted vehicle control of UAVs by airborne assets	6
Improved algorithms and techniques for autonomous control of groups of unmanned marine vehicles	6
Capability upgrades to helicopter and UAS data link	6
Adapting a digitally fused sensor system to a UAV platform	7

3. Security

News reports of UAVs being hijacked by adversaries emphasize the need for increased security measures. The Roadmap (2013) stated that the “emphasis has shifted from protecting system-organic technologies and information to a more comprehensive

methodology: a platform agnostic, sensor-specific approach to address program protection across multiple systems and platforms” (p.58). The Roadmap (2013) also stated that “anti-tamper is also more cost effective when implemented at program onset” (p. 58), which could present a barrier to smaller companies at the onset.

As shown in Table 4, security technologies found in the IR&D database are still immature. The first TRL listed, “develop resilient system to cyber, jamming, and physical attacks” is still at level 2, emphasizing the time, effort, and funding still needed to advance this very immature technology.

Table 4. Security Technology Summary (after J. W. Smith, personal communication, September 9, 2013)

Develop resilient system to cyber, jamming, and physical attacks	2
Develop Anti-Jam/EW Antenna Array processing algorithms for low-SWAP UAVs	2
Capability in the field of transmission security (TRANSEC) and cryptography for space and high altitude persistent loitering asset applications	3
Mitigation of malware code threat to unmanned systems	3
Fiber optics that provides electro-magnetic interference (EMI) protection against energy weapon attacks & against faster bus architectures	3
Low radar cross section anti-electronic warfare UAV antenna	5

4. Persistent Resilience

The Roadmap (2013) defined *persistence* as “the continuance of an effect” (p. 62) and resilience as “the ability for an application system, or subsystem to react to problems in one of its components and still provide the best possible service” (p. 62). The DoD is constantly searching for “efficient solutions to the demand for improved propulsion and power plants” (*FY2011–2036 Unmanned Systems*, 2011, p. 29). The Roadmap (2013) broke this category into five subcategories:

1. Size, Weight, Power, and Cooling
2. Reliability, Availability, and Maintainability
3. Survivability
4. Structures and Material Degradation
5. Propulsion

Table 5 contains TRLs for persistent resilience technologies. Technologies in this category are on average more mature than other categories, but the potential for breakthrough innovations, such as improved fuel cells or advanced materials, means this category could be in a state of constant flux

Table 5. Persistent Resilience Technology Summary (after J. W. Smith, personal communication, September 9, 2013)

Advanced military propulsion systems and enabling technologies concentrating on subsonic, supersonic, and hypersonic systems, including land and sea based vehicles	1
Identify improvement in the Thermal Management System (TMS) required to meet payload bay ambient requirements	2
Supercritical fuel injection	3
Advanced propulsion and auxiliary power generation	3

technologies	
Component and materials technologies directed at enhancing the Versatile Affordable Advanced Turbine Engine (VAATE)	4
Derivative and new centerline advanced technology engine candidates for near-term rotorcraft applications, and advanced propulsion technologies that meet future UAV and rotorcraft propulsion system requirements	4
Heavy fuel/multi-fuel high power density engines	5
Unmanned undersea system cryogenic storage and delivery system for hydrogen and oxygen fuel cell reactants	5
Centerline advanced technology engine candidates for near-term rotorcraft applications, and advanced propulsion technologies that meet future UAV and rotorcraft propulsion system requirements	6

5. Autonomy and Cognitive Behavior

The Roadmap (2013) highlighted autonomy as one of the most critical areas for development. Autonomy is listed as one of the seven science and technology emphasis areas by the DoD Research and Engineering Enterprise. As stated in the introduction, unmanned aircraft are much cheaper than the manned airframes they are designed to replace, but the manpower requirements are not necessarily fewer. Increased autonomy will decrease manpower requirements, thereby decreasing the overall cost of unmanned programs. The 2011 Roadmap defined autonomy as “self-steering or self-regulating and is able to follow an externally given path while compensating for small deviations caused by external disturbances” (OSD, 2011, p. 43). An autonomous system is “able to make a decision based on a set of rules and/or limitations” (*FY2011–2036 Unmanned Systems*, 2011, p. 43) and “is able to determine what information is important in making a

decision” (*FY2011–2036 Unmanned Systems*, 2011, p. 43). The updated Roadmap (*FY2013–2038 Unmanned Systems*, 2013) focused on mission performance vice mission execution, where execution is the accomplishment of a preprogrammed plan, whereas performance is “associated with mission outcomes that can vary even during a mission and require deviation from preprogrammed tasks” (pp. 67–68). Figure 43 is from the 2011 Roadmap, which was not updated in the 2013 Roadmap.

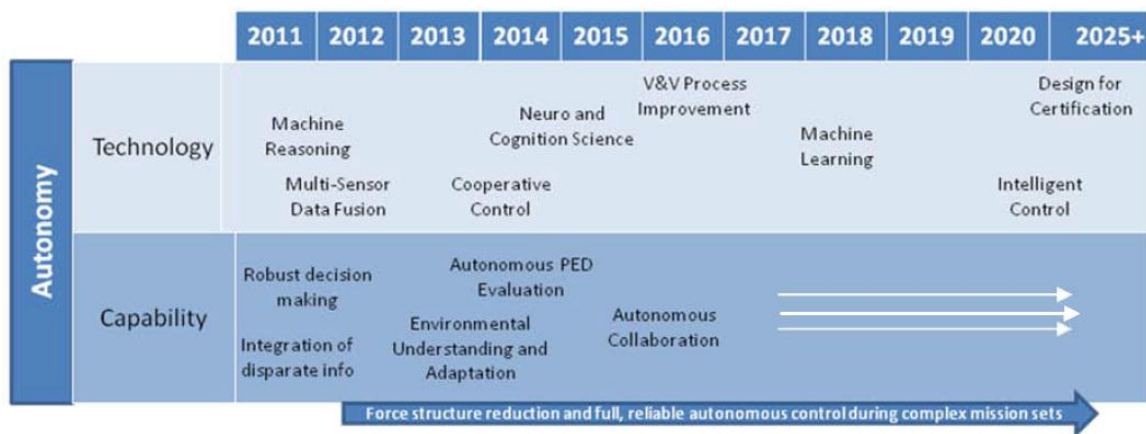


Figure 43. Autonomy Roadmap (from *FY2011–2036 Unmanned Systems*, 2011)

Table 6 shows TRLs for autonomy technologies in the IR&D database. Like the communications category, autonomy has one of the highest concentrations of immature technologies. The second technology listed provides the overall status of autonomy efforts, and shows that one of the highest profile technologies is still very immature and will require time and resources to advance.

Table 6. Autonomy and Cognitive Behavior Technology Summary (J. W. Smith, personal communication, September 9, 2013)

Autonomous Systems Pathfinder initiative to develop a next-generation urban unmanned aerial system	1
Creation of effective perception systems for robots and	2

unmanned vehicles, which is based on the representation that unifies real-world perceptual and conceptual information on a single basis, and this allows for their processing on a single basis in real time	
Autonomous robot navigation and manipulation technology to enable robot to retrieve objects of interest	2
Develop flexibly autonomous systems with certifiable trust through verification and validation	2
Real-time computation of contingency aircraft trajectories	3
Scalable Autonomy Sensors that integrate heterogeneous sensors to provide autonomy for a robotic platform	3
Adaptive control	3
Addressing autonomy capability gaps in the context of an anti-access/area denial (A2/AD) scenario	3
Algorithms and software that span real-time depth from stereo imagery, structured light exploitation, simultaneous localization and mapping (SLAM)	3
Common, verified and validated, certifiable algorithms for collaborative control of autonomous vehicles	4
Undersea robotics in support of mine warfare and other undersea warfare missions	5
UAS integration technologies that support covert UAS missions	6

Autonomous underwater vehicles that are capable of performing both inspection missions and operations in deep water	7
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6. Weaponry

Table 7 shows TRL levels for weapons technologies. The focus of weaponry for unmanned systems is the effectiveness to weight ratio, since the munitions must be light enough to be carried on small unmanned systems. The Roadmap (*FY2013–2038 Unmanned Systems*, 2013) emphasized that no current weapon systems was designed to be employed from unmanned systems. The DoD will also focus on development of unmanned systems as weapons themselves, particularly for the suppression of enemy air defenses.

Table 7. Weaponry Technology Summary (after J. W. Smith, personal communication, September 9, 2013)

Weapon system characteristics and capabilities required by next generation aircraft platforms such as the UCAV	1
Determine feasibility of laser designation/illumination pointing accuracy from a small unmanned aerial vehicle (UAV) platform	2
Directed energy laser for self-protection purposes	3
High-energy laser (HEL) weapon system	3
Enhanced energetics and ordnance for incorporation in small munitions (primarily UAV based)	4

7. Other Unmanned System TRLs

Table 8 depicts TRLs for technologies in the IR&D database that did not clearly fit into one of the above categories. This table contains TRLs for some of the lower priority categories, such as sensor air drop and weather sensing, and TRLs for specific systems.

Table 8. Other Unmanned Systems Technology Summary (after J. W. Smith, personal communication, September 9, 2013)

A flexible approach for use by both military and civilian organizations to assess the hostile intent of red UAS	1
A study for potential commercial market opportunities for an airborne ISR system	1
Approaches to re-architect Global Hawk operations and support concepts that reduce costs yet maintain mission effectiveness	1
Capability to precisely place and sense and retrieve sensor packages	2
Assess suitability of Cobra unmanned vehicle for the Littoral Combat Ship Unmanned Surface Vehicle mission.	2
Perform mishap and incident investigations and apply corrective actions on available air vehicles	2
System Safety, Safety Critical Validation & Verification planning and execution, and other airworthiness tasks supporting certification of the Global Observer UAS	2
Further development of the VTOL SUAS to satisfy anticipated customer requirements	2
Provide early warning of dangerous chemical, biological, radiological, nuclear, and high-yield explosives (CBRNE) plumes, to identify them, and to map/track them	2
Advance the technology readiness level of a very compact low power microprocessor design	3

Estimate the external wind velocity on a vehicle, and thus things like true air speed, angle of attack, and side slip, without having dedicated air data sensors such as probes	3
Combine above water and below water sensor data to generate a 3D perception map of the world around the target platform	3
MURAL (Manned Unmanned Resupply Aerial Lifter) and other optionally piloted rotorcraft capabilities	3
Design and development of a Global Hawk generic payload pod	3
Bonded structures and joining concepts for future DoD composite airframes	4
Advanced control surfaces	4
Nanoparticle technology for advanced materials	5
Additive fine line metallization of flex circuit technology	6
New low-cost, light-weight, mini-pod for UAS payloads	6
Bi-phasic (capable of maneuvering in air and water) unmanned vehicle	6
Improving Cargo UAS to more effectively augment ground and air logistics operations	6
Unmanned robotic platform for carrying soldiers' mission essential equipment	7

C. DOMINANT DESIGNS IN THE CURRENT INDUSTRY

The data suggest that the DoD has identified at least two dominant architectural designs in the unmanned systems industry, both in the UAV sector. The RQ-4 Global Hawk/MQ-4 Triton and MQ-1 Predator/MQ-9 Reaper configurations are being adapted to various missions and receive the majority of funding for unmanned systems development and procurement. The DoD is in the process of selecting a design for the UCLASS carrier-based UAV, which will receive billions of dollars of funding for R&D and procurement over the next few years.

The dominant design of an unmanned system has relatively few characteristics. Unmanned architectures require the ability to be securely controlled remotely, a propulsion system, and payload capability for sensors, weapons, or robotic systems. UAVs also add the requirements of a lift-producing wing and launch and recovery capability. If one decides that the dominant design has been attained, the process switches from exploration of alternatives to exploitation of the chosen design. As noted in the literature review, this has very important ramifications to the continued evolution of the industry.

Given the immaturity of the industry, it is difficult to argue that the Global Hawk and Predator architectures are dominant designs. It is critical that unmanned systems be more cost effective than comparable manned designs, and this point is of greatest concern.

The most recent Program Acquisition Unit Costs (PAUC) of the Global Hawk and Predator architectures are depicted in Table 9. These values are provided in Selected Acquisition Reports to quantify cost per copy and provide a baseline for cost growth comparison. The PAUC is computed by dividing the Program Acquisition Cost by the Program Acquisition Quantity. Program Acquisition Cost is the sum of RDT&E, procurement, and unique military construction costs. The program acquisition quantity is the total procurement quantity plus RDT&E prototypes that are used for Initial Operational Test and Evaluation. PAUC is not a perfect measure for airframe cost comparison since it does not take into account some life-cycle costs that provide better

measures of affordability. However, PAUC is the clearest and least manipulable estimate for weapon system cost. To better account for program O&S costs, Table 9 also depicts cost per flying hour for each airframe.

Table 9. Cost per Copy of Selected UAVs from December 2012 Selected Acquisition Reports (after DAMIR Database, 2013; Oestergaard, 2013; Shalal-Esa, 2013; Vitasek et al., 2006)

All values in FY2014 Dollars		
Variant	PAUC	Cost Per Flying Hour
MQ-1B Predator	\$15.1 million	\$3,242
MQ-9 Reaper	\$30.8 million	\$4,762 estimated
RQ-4A/B Global Hawk	\$214.5 million	\$18,900 estimated
MQ-4C Triton	\$189.4 million	N/A
For comparison, the following data are provided:		
RQ-7 Shadow UAV	\$764,000	\$366 estimated
F/A-18E/F Super Hornet	\$105.7 million	\$16,000 estimated
AV-8B Harrier	\$37.15 million	\$11,134

For comparison, the most recent PAUCs and estimated costs per flying hour for the RQ-7 Shadow, F/A-18E/F, and AV-8B Harrier are included. The MQ-4C Triton is still in development; therefore, reliable cost per flying hour data does not yet exist. Of note, a recent report (Shalal-Esa, 2013) stated that the RQ-4 Global Hawk cost per flying hour has dropped more than 50% since 2010 due to increased usage and improvements in contractor logistics support.

The PAUC provides an estimate of acquisition cost per system, while the cost per flying hour is an estimate of the cost to employ the system. The cost for the Predator

variants is comparable to legacy airframes like the AV-8B Harrier, while Global Hawk variants are comparable to some of the most sophisticated manned aircraft. Even the highly successful Shadow UAV costs more than \$750,000 per copy, although its cost per flight hour is significantly lower than the other UAVs. These airframes could hardly be considered expendable, especially in the current fiscal climate.

Figure 44 depicts funding for the three largest UAV programs as a percentage of total unmanned systems funding from FY2014 through FY2018. Data for the three UAV programs come from the IHS Jane's Budget Analysis (2013), and these data are compared to total unmanned systems budget data from the 2013 Roadmap (*FY2013–2038 Unmanned Systems*, 2013). In FY2014, funding to the three largest UAV programs is almost 50% of total unmanned systems funding. After FY2014, this percentage increases to over 50% and continues to grow through FY2018. Importantly, the funding information for the three UAV programs does not include O&M cost forecasts, which would increase their percentage of total unmanned systems funding. O&M costs are included in the Funding for other UAV Programs and Total Non-UAV Funding categories.

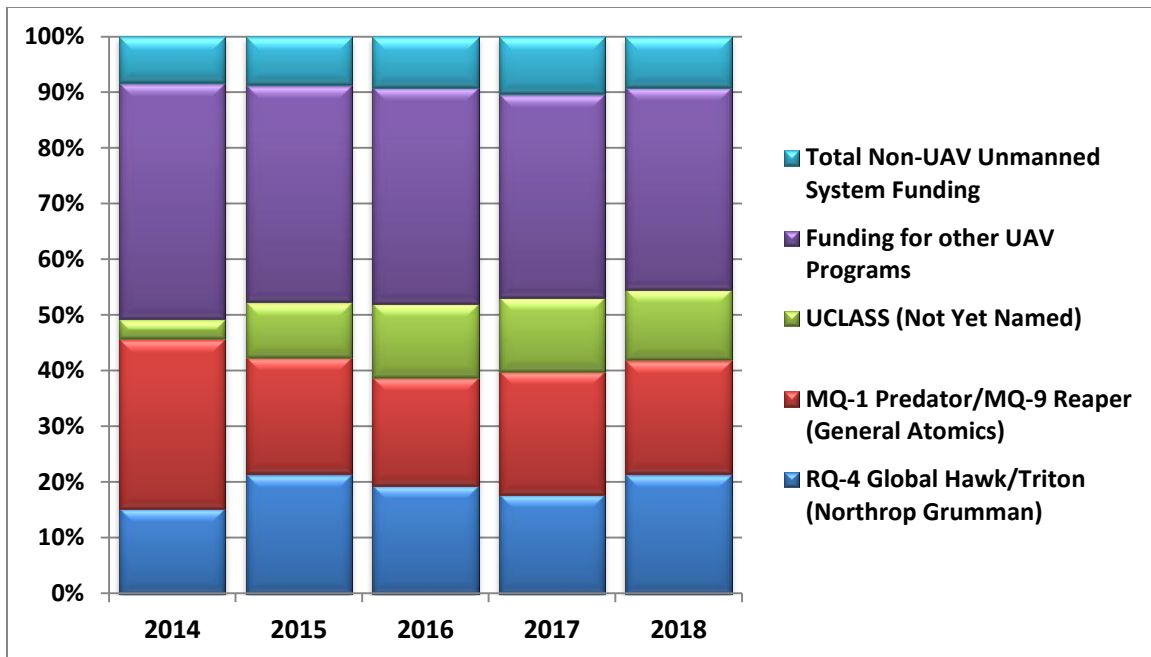


Figure 44. Funding for Select UAV Programs as a Percentage of Total Unmanned Systems Funding FY2014–2018 (after IHS Aerospace, Defense, & Maritime, 2013; *FY2013–2038 Unmanned Systems*, 2013)

The data show that over 50% of total unmanned systems funding through FY2018 will go to three prime contractors: General Atomics, Northrop Grumman, and the yet-to-be-named producer of the UCLASS. This trend will hasten industry consolidation and likely decrease competition and innovation in the UAV industry.

The Roadmap (*FY2013–2038 Unmanned Systems*, 2013) emphasized the importance of innovation to the unmanned systems industry, stating:

In particular, the ability of unmanned assets to take risks that would not be taken with manned assets opens up new CONOPS, such as low-cost, expendable systems that trade armor and stealth for quantity. In other words, a fleet of low-cost, disposable platforms could survive through attrition rather than through expensive, exquisite capabilities. (pp. 18–19)

Likewise, the DoD vision for unmanned systems is the fielding of “affordable, interoperable, integrated, and technologically advanced” (*FY2013–2038 Unmanned Systems*, 2013, p. 1) capabilities. While the three major UAV programs are certainly technologically advanced, they are definitely not low cost or expendable. The increase in funding to the three large UAV programs means a decreasing share of funding for

exploration of low-cost, expendable designs that will constitute the future force. The Roadmap (*FY2013–2038 Unmanned Systems*, 2013) discussed the potential of the civilian market to drive innovation for small unmanned systems development, but U.S. government policies might mean that this innovation takes place overseas, not here on U.S. soil.

D. THE UNMANNED SYSTEMS INTEGRATED ROADMAP VERSUS THE BUDGET CHAPTER SUMMARY

The DoD has emphasized the importance of the unmanned systems industry to national security, and budget information confirms the DoD's intent. While the DoD will significantly cut funding to many programs, funding for unmanned systems R&D and procurement remains relatively healthy, although in general decline. The quantity of funding to the unmanned systems industry is critical, but more important is how the DoD will spend the resources. Will the spending be focused on larger companies exploiting current technologies, or will the DoD continue to distribute the funds among many players in the interest of fostering continued innovation and competition? Exploitation of existing technologies could bring costs down in the short term but could result in the fielding of technologically obsolete systems in the face of exponential global industry growth where market forces mature current technologies and provide disruptive innovations that revolutionize the industry.

The immaturity of many unmanned systems technologies is a significant concern at this point. Although unmanned systems have performed well in Iraq and Afghanistan, they benefitted from a low denial threat. In order for unmanned systems to be used in more contested environments, or to decrease unmanned system costs and manpower requirements, there are huge technology gaps that must be closed. Although most unmanned systems are cheaper per copy than manned systems they are designed to replace, manpower requirements are typically not fewer, which keeps operations and maintenance costs high. In order to realize greater cost effectiveness, the DoD will have to make huge leaps in autonomy and persistent resilience technologies, which are still immature.

The fact that over 50% of total unmanned system funding is going to only three programs is alarming, considering the DoD emphasis on innovation and expendability. The data show that the DoD is already narrowing down on select technologies at the expense of exploration. The share of the fiscal pie available for exploration and development of breakthrough architectural technologies is decreasing each year. The growth potential of the civilian unmanned systems market is clear, but regulatory policies threaten industry health while DoD funding continues to decline.

VII. SUMMARY, CONCLUSIONS, RECOMMENDATIONS FOR FUTURE RESEARCH

A. SUMMARY

U.S. intervention in Afghanistan will draw to a close in the near future. The U.S. government has already factored the drawdown into future budget assessments, and there will be increased pressure to cut spending across the board, especially in the DoD. Efforts to achieve commonality and efficiencies, such as with the JSF, could reduce innovation and competition in the fledgling unmanned systems industry. It is dangerous to juxtapose the current unmanned systems industry and the current fixed-wing aviation industry in arguments for industry consolidation, since the industries are at very different levels of overall technological maturity.

The data in the Individual Program Funding Detail section indicate that narrowing down on certain designs is already in progress, especially in the UAV sector. However, given the immaturity of the robotics industry, the research suggests this narrowing down comes at great risk. Admittedly, the desire to incorporate stealth technology and other expensive initiatives requires the selection of few designs at the expense of others, but tying up funds with certain programs reduces the chance that the DoD is able to realize the next disruptive innovation. The most revolutionary design in UAV architecture was built in an inventor's garage, and given the infancy of the industry, there will likely be more innovative breakthroughs.

The research shows that the U.S. unmanned systems industry is as healthy now as it has ever been, with more firms receiving the highest level of funding in history. The prospects of commercial demand are very appealing and indicate a possible shift of responsibility for maturation from the DoD to the commercial market. However, there are still significant barriers to this commercialization; therefore it is imperative that the DoD not relinquish responsibility for development too early, lest it fall on a still immature industry burdened by U.S. government policies that will harm the industry for years to come. I believe that the current unmanned systems industry resembles the fixed-wing aviation industry at the Armistice, where decisions the government makes post-conflict will have critical and far-reaching effects on the U. S. unmanned systems industry.

Although the civilian market demand for unmanned systems will continue to grow, certain sectors will still be limited to DoD research, including stealth technology and weapons system employment. The DoD will ignore research in unmanned systems at its own peril. As the DoD withdraws combat forces from Afghanistan, U.S. unmanned systems testing will shift from the defense sector to the commercial sector. The locus of learning will shift, and DoD learning will be indirect rather than direct.

This research shows that overall funding for unmanned systems R&D and procurement is relatively stable, and budget forecasts through 2018 are healthy despite impending cutbacks. However, total annual funding for unmanned systems is still a fraction of the total funding for large programs like the JSF over the next five years. Given the relatively small percentage of funding, *how* the DoD spends resources will be critical. Over 50% of total unmanned systems funds will be locked up in three programs for the next five years. Locking funds into long-term, costly programs can result in failure to identify and explore breakthrough technologies that revolutionize the industry. The global commercial industry is now realizing unprecedented demand. Similar to the VHSIC vignette, if the DoD locks itself into drawn-out programs, it could be fielding obsolete technology while the commercial market or rival nations outpace it.

B. CONCLUSION

Given the immaturity of the industry, the DoD should increase funding to unmanned systems development and procurement, focusing more on exploration and RDT&E until U.S. government policies that inhibit civilian market growth are mitigated. The DoD should closely examine its policy of narrowing down on few designs, which consumes resources that could be spent on identifying breakthrough technologies.

In this era of budget crises and military drawdowns, the call to increase funding to a particular area will almost certainly induce eye-rolling. However, I base this conclusion on the following factors:

- Unmanned systems are the future, and the DoD must remain dedicated to them despite the cost. Unmanned systems funding is less than 1% of total DoD funding, despite insistence that unmanned systems development is a priority.

- U.S. government policies, such as export controls and airspace restrictions, hinder civilian market growth critical to advancing the state of the art. Other nations do not face this level of restrictions and will take advantage of this to close the technological gap. The advantages enjoyed by the U.S. in focused development will be diminished as combat operations wind down.
- The DoD should make no determined effort at industry consolidation or narrowing down on few designs. Narrowing down too early in an immature industry could result in fielding obsolete technology. The fact that over 50% of total unmanned systems funding will be going to only three UAV programs should raise red flags to those concerned about competition and innovation.
- Once key developments are made in autonomy and other areas, unmanned systems will be more cost effective than manned systems performing similar missions and will reduce unnecessary risks to U.S. personnel. These developments require more resources now, but will result greater long-run cost savings as advanced technologies minimize O&M requirements. The most difficult cost to quantify is the value of the human lives spared by these technologies.
- Although some development redundancy has occurred by competing firms with DoD contracts, this should not be viewed as wasting resources. The importance of building a sound technological base cannot be overstated.
- Unmanned systems are uniquely poised to take advantage of streamlined acquisition processes that are greatly desired in the push for acquisition reform.

C. RECOMMENDATIONS FOR FUTURE RESEARCH

As combat operations in Afghanistan draw to a close, the DoD will inevitably focus on unmanned systems consolidation. While more unmanned systems variants mean more experimentation, there are training, operations, and maintenance costs associated with each variant. Further research could focus on identifying the costs associated with maintaining multiple unmanned variants.

Although the Unmanned Systems Integrated Roadmap (*FY2013–2038 Unmanned Systems*, 2013) identified unmanned ground systems as a priority, the funding for such systems is a small fraction of total unmanned systems funding. I recommend research on the DoD strategy to meet Roadmap objectives with such limited funding.

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APPENDIX A. TECHNOLOGY READINESS LEVEL DEFINITIONS

Table 10. Technology Readiness Level Definitions, Descriptions, and Supporting Information (from Assistant Secretary of Defense for Research and Evaluation [ASD(R&E)], 2011)

TRL 1 Basic principles observed and reported: Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.

TRL 2 Technology concept and/or application formulated: Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.

TRL 3 Analytical and experimental critical function and/or characteristic proof-of concept: Proof of concept validation. Active Research and Development (R&D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.

TRL 4 Component/subsystem validation in laboratory environment: Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.

TRL 5 System/subsystem/component validation in relevant environment: Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.

TRL 6 System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space): Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.

TRL 7 System prototyping demonstration in an operational environment (ground or space): System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.

TRL 8 Actual system completed and “mission qualified” through test and demonstration in an operational environment (ground or space): End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.

TRL 9 Actual system “mission proven” through successful mission operations (ground or space): Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

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APPENDIX B. 2013 UNMANNED SYSTEM PRIME CONTRACTORS

Table 11. 2013 DoD Unmanned Systems Prime Contractors (from OSD, 2013)

2013 Unmanned Systems Prime Contractors	
Company	Unmanned Systems
AAI Corporation	RQ-7B Shadow
AeroVironment	RQ-20A SUAS (Puma), RQ-11B Raven B, Wasp,
Applied Geo Technologies	MARCBot IV N
Applied Research Associates -Vertek Division	All-Purpose Remote Transport System (ARTS),
Applied Research Laboratory, Penn State University	Sea Maverick, Sea Stalker
Boeing	ScanEagle, Echo Ranger,
Bluefin Robotics	Hull Unmanned Underwater Vehicle Localization System (HULS)
Caterpillar	Automated Ordnance Excavator (AOE)
DOK-ING	M-160,
Foster-Miller	MK 2 MOD 0 Robot EOD,
General Atomics	MQ-1C Gray Eagle, MQ-1B Predator, MQ-9A Reaper
General Dynamics Advanced Information Systems	Surface Mine Countermeasures Unmanned Undersea Vehicle (SMCM UUV)
General Dynamics Robotics Systems	Antisubmarine Warfare Unmanned Surface Vehicle (ASW USV)
Harborwing	Autonomous Unmanned Surface Vehicle (AUSV)
Honeywell International	RQ-16B T-Hawk
Hydrema	Mine Area Clearance Equipment (MACE)
Hydroid	MK 18 MOD 2 Kingfish, MK 18 MOD 1 Swordfish
Insitu Incorporated	RQ-21A STUAS
iRobot	Mini EOD, MK 1 MOD 0 Robot EOD, PackBot 510,
L-3 Unmanned Systems	Viking 400,
Lockheed Martin	Persistent Threat Detection System, Marlin, Remote Minehunting System (RMS), RQ-170 Sentinel,
Northwind Marine	SEAFOX
NSWCCD & NSWC PC	MUSCL
Northrop Grumman	MQ-8B VTUAV (Fire Scout), MQ-5B Hunter, MQ-4C Triton, RQ-4B Global Hawk, Long Endurance Multi-Intelligence Vehicle (LEMV), MK 3 MOD 0 Remote Ordnance Neutralization System (RONS), F6A ANDROS, HD-1, X-47B UCAV
Oregon Iron Works	Mine Countermeasures Unmanned Surface Vehicle (MCM USV)
PFM Manufacturing	Defender, Fire Robotics Platform
QinetiQ (Foster-Miller)	TALON IIIB, TALON IV,
Raytheon	Joint Land Attack Elevated Netted Sensor System (JLENS)
Recon Robotics	Recon Scout XT
Segway	Immediate Visualization and Neutralization (IVAN)
SSC Pacific (With multiple vendors)	ISR Unmanned Ground Vehicle (UGV),

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